DOCTOR OF HEALTH (DHEALTH)

Spinal, Pelvic and Lower Limb Kinematics. A Pre and Post Injury Comparison of Elite Level Football Players

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Paul Bell

A thesis submitted for the degree of Doctorate in Health

University of Bath

Department of Health

August 2018

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Signature of author...Paul Bell

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Acknowledgements

I wish to thank a number of people for their contribution to completion of this thesis.

I would like to thank the Singapore Football Association and in particular the players who volunteered to participate in the study. In addition, my thanks go to Balder Berckmans, the strength and conditioning coach, who showed great enthusiasm for the project and was invaluable in gaining access to and being a gatekeeper for the participants.

My work colleagues at The Osteopathic Centre who volunteered to help by taking part in the Pilot study and assisting during the data capture process.

Dr Monica-Cristiana Hess for her advice for certain aspects of the statistical analysis process.

Mr Derek Holland for his exhaustive knowledge of the English language.

My sincere thanks go to my supervisor Dr Cassie Wilson for her guidance. She has provided a sounding board for ideas, patiently given feedback on the revisions of the revised revisions and helped me to visualise the study macroscopically. This thesis would have been a shadow of its present self without her knowledge, help and support.

Last but certainly not least; I would like to thank my wife Clare. She has walked the long road with me to completion of this thesis. Given up weekends and activities, taken more of the load so I could concentrate on the research, listened, supported and not even raised an eyebrow when I have shouted and cursed at my laptop, and she doesn't even get a certificate at the end of it all! This thesis, and my life, would not be complete without her.

Abstract

Sports injury and re-injury is a common occurrence; however, the kinematic mechanisms that predispose or adaptations that follow injury are often poorly understood. Therefore, the aim was to examine spinal and lower body kinematic movements over time and as a response to injury during a sub-maximal inside-of-the-foot pass kick.

An observational based prospective single cohort study was undertaken to analyse the kinematics of 29 elite level footballers. Participants underwent repeated measures (two) assessments six months apart utilising a markerless motion analysis system with progressive separation during the trial period into injured and non-injured groups dependent on injury occurrence. Group and individual statistical and descriptive comparisons were undertaken. An individualised Functional Movement Profile (FMP) was created for each participant to facilitate improved intra-individual assessment.

Analysis of the first assessment data demonstrated that reduced mean thoracic flexion and increased support knee flexion-pelvic side bend variability may have a predictive relationship with future injury occurrence. The kinematic strategy employed to complete the task was varied and changed over time in both groups but in the injured group the coupled angle variability of support leg knee flexion-pelvic side bend was greater during both assessments and reduced significantly over time. In addition, lumbar lateral flexion and thoracic rotation were greater in the injured group during both assessments. Adaptation occurred over time to the 'normal' movement strategy employed by the injured group when completing the task, which may be indicative of compensatory mechanisms following injury.

Spatiotemporal analysis identified that kicking hip flexion, pelvic side bend and lumbar flexion and the coupled angle variability of pelvic rotation-thoracic rotation changed significantly in the non-injured group over time.

Both inferential and descriptive analysis identified notable disparity between the injured and non-injured participants and between the mean group movement ('norm') and individual movement patterns. Therefore intra-individual assessment and utilisation of Functional Movement Profiles is recommended as a useful and important analytical approach to help realise the full impact of intra-individual kinematic change over time and as a response to injury during functional tasks.

List of Abbreviations

ACL	Anterior Cruciate Ligament
ANOVA	Analysis of Variance
cm	Centimetres
COM	Centre Of Mass
CV	Coefficient of Variation
FMP	Functional Movement Profile
FMS™	Functional Movement Screening
ICC	Intraclass Correlation Coefficient
Kg	Kilograms
LBP	Lower Back Pain
LESS	Landing Error Scoring System
LEX	Lower Extremity
MAD	Mean Absolute Deviation
MAD_{es}	Mean Absolute Deviation Effect size
NMST	Netball Specific Movement-Screening Tool
$iMAD_{es}$	Independent groups Mean Absolute Deviation Effect size
$dMAD_{es}$	Dependent groups Mean Absolute Deviation Effect size
MRI	Magnetic Resonance Imaging
OSICS	Orchard Sports Injury Classification System
ROM	Range Of Motion
SD	Standard Deviation
SIMS	Soccer Injury Movement Screen
SPM	Statistical Parametric Mapping
SPM(t)	Scalar Output Statistic
STS/STS	Sit-to-Stand/Stand-to-Sit
3D	Three-Dimensional

Further abbreviations used in the results section are included in Table 2, Page 59.

Chapter 1 Introduction

1.1 Research Overview

Injury is an extremely common occurrence in sport especially in the dynamic sports environment. When an athlete is injured there is the obvious and immediate issue of experiencing pain and dysfunction and the possibility of short term and, in some instances, prolonged psychological distress (Leddy, 1994, Roderick, 2006). In addition, injury may have a notable effect on personal and or team performance (Hägglund, 2013) and in the professional sports environment, injury could affect the athlete's income earning potential and career prospects (Secrist, 2016). It is arguable, considering the negative effect on participation and the increased physical and psychological effects experienced (Hsu, 2017, Kvist, 2005, Swenson, 2009) that recurring injuries may have even greater and further-reaching detrimental implications for the athlete. In this context, when considering the training and competition time lost due to injury (Brooks, 2005) and the increased severity and prolonged recovery periods associated with recurring injuries (Swenson, 2009), the question must be asked 'can more be done to reduce the risk of sports injury and re-injury'?

Practitioners in the fields of sports biomechanics, sports science and sports medicine are constantly searching for answers to explain the how and why, in an attempt to improve our understanding and ability to predict and prevent sports injuries. A method commonly employed in an effort to predict and thus reduce the incidence of sports injury is motion analysis. The aim of this approach is simple in theory; examine how the athlete moves or performs a task and if the movement is incongruent to 'normal' movement patterns (Bartlett, 2007) then an intervention can be prescribed. These interventions will attempt to address the 'abnormal' movement pattern and return optimum function. Whilst the theory is sound, practical application of this approach is complicated by a number of issues. It may be difficult if not impossible to identify what constitutes a 'normal movement pattern' (Brisson, 1996, Fox, 2014). There is some disagreement regarding the clinical relevance of motion analysis for injury intervention (Bartlett, 2005, Elliott, 2002, Simon, 2004) and argument as to which approach constitutes the utopian motion analysis method i.e. a method that optimally combines accuracy, ease of application and time efficiency. It is the opinion of this author that as yet this ‘perfect motion analysis method’ does not exist. However, the benefits of employing human motion analysis are generally accepted and it is employed broadly and in its many forms in the sports environment (Ford, 2007, Requena, 2012, Sato, 2012, Shan, 2011).

As discussed, motion analysis has been employed extensively in the sports environment as an injury prevention tool. A prime example being the numerous investigations exploring biomechanical perturbation at the knee and its possible correlation to increased risk of knee injury (Hewett, 2015, Hofbauer, 2014, McLean, 2005, Padua, 2009). In addition to improving our understanding of biomechanical changes that occur locally at a joint, motion analysis has also opened a window onto the biomechanical interactions of various regions of the body and the potential role that ‘regional interdependence’ and compensatory adaptations may play in injury occurrence (Barnett, 2013, Hewett, 2009, Paterno, 2010, Sheehan, 2012, Vaughn, 2008, Wainner, 2007, Zazulak, 2007a)

Our knowledge of how the spine responds to pain and injury especially in a chronic state is relatively well developed (Gregory, 2004, Hodges, 2003). Unfortunately despite the potential importance of regional interdependence, only limited research has investigated correlations between the spine and lower extremity (LEX) in respect to changes in function as a consequence of injury (Mohammadi, 2012, Nadler, 1998, Tecco, 2002). There is need for further investigation of the longer-term adaptations that may occur in the spine as a result of regional interdependence following recovery from injury and the possible repercussions of such adaptive effects (Tecco, 2002). This is especially true regarding our understanding of spinal adaptations in the sports environment that may impact specific functional tasks and could possibly lead to performance deficit (Nadler, 2002) or increased injury risk (Seay, 2011b). Useful assessment procedures have been developed to gather information about the functional interaction of interconnected body regions (Cook, 2014a); however these procedures do not specifically examine spinal kinematics and to date still lack unequivocal proof of efficacy in regards to injury prediction (Dorrel, 2015). More accurate and specific analysis approaches do exist, such as the employment of marker–based 3D analysis systems (Tokuyama, 2005) but these systems can be prone to user induced error (Schache, 2002) and are relatively time-intensive to use (Ceseracciu, 2014). Perhaps, as Bartlett (2005) proposes, there is the need to develop new motion analysis procedures in

order to fully understand the relationship between alterations in spinal biomechanics and injury, and to identify if this correlates with increased risk of re-injury. These new procedures would need the capacity to accurately capture, analyse and compare movements that are unique to the individual during the specific task be time efficient and capable of reducing levels of error during use (Ball, 2003, Bartlett, 2005).
As described, insufficient investigation has been undertaken to assess the extent of spinal kinematic alterations that are maintained following resolution of injury. In respect to the current investigation, the main focus of interest was lumbar and thoracic spinal kinematic adaptations. However, considering the potential role of regional interdependence, the effect on spinal kinematics following injury to the pelvis and or LEX was also considered as it was deemed potentially potent to any spinal kinematic changes that may be identified (Scholtes, 2009, Seay, 2011b, Shan, 2005, Song, 2012, Zazulak, 2007b).

1.2
Research Questions

1. **What are the normal kinematics during the sub-maximal inside-of-the-foot pass kick?**

Often in coaching and sports injury environments the way an individual moves whilst kicking is compared to a 'normal' or 'ideal' kicking technique; however, limited exploration has been undertaken to identify the kinematics that accurately represent this 'norm' or even if the ideal movement actually exists.

2. Do kinematics differences exist in players who experience injury?

It is necessary to quantify if kinematic markers that have injury predictive value can be identified during baseline assessments.

3. Do kinematic adaptations during kicking occur in elite level football players over an extended period of time?

In order to estimate the effect of injury on kinematics (compensatory mechanisms) it is necessary to quantify not only what constitutes normal movement but also how movement may change, independent of injury over an extended period of time.

4. Is markerless motion capture technology suitable for measurement of a sport specific task?

Although markerless approaches to movement analysis have been employed previously, further evidence is required to substantiate the ability of this approach to measure sports specific dynamic functional tasks.

5. Can the data from such analysis be used as an accurate injury predictive tool?

If the markerless motion analysis system is capable, then is the data it can provide suitable to guide clinical interventions?

6. Is an individualised functional movement profile an appropriate tool to assess kinematic adaptations during a sports specific task?

It has been suggested that rather than group comparison, individualised analysis and intra-individual comparison is the more accurate approach for kinematic analysis. If this is the case are functional movement profiles a suitable tool to facilitate this process?

7. Do compensatory mechanisms lead to altered spinal kinematics in elite level football players that have returned to pain-free activity following spinal, pelvic or lower limb injury?

In regards to kinematic response to injury, ‘compensation’ and ‘compensatory’ are terms that are widely used in the sports injury environment. However, the mechanisms underlying this ‘compensation’, that is the how and why one region affects another, are under-researched and poorly understood.

1.3

Statement of Purpose

The underlying biomechanical mechanisms that lead to injury and the adaptations that occur following recovery from injury are poorly understood. This study sets out to investigate if changes in kinematic movement patterns could be used to predict injury and also to investigate kinematic adaptation over time and as a response to injury.

In order to accomplish this it was necessary to achieve the following five objectives:

(i) Undertake group and intra-individual baseline kinematic measurements (Bartlett, 2007) during the sub maximal inside-of-the-foot pass kick to facilitate comparative analysis between groups and creation of intra-individual 'functional movement profiles' (FMP) for this task.

(ii) Identify patterns of kinematic movement that may be applicable for use as injury prevention markers.

(iii) Assess normal kinematic adaptations that may occur, i.e. changes in group scores or the intra-individual FMP scores over an extended period of time; in this case a period of six months between initial and secondary data collections.

(iv) Utilise the group and FMP data collected to examine if injury in the spine, pelvis or LEX effects spinal movement beyond any normal adaptations that may have occurred.

(v) Ascertain the value of using the FMP for intra-individual kinematic data analysis.

To achieve these objectives a markerless motion analysis system was employed to examine a sports specific task and analyse kinematic movement patterns.

1.4

Organisation of Thesis

Following an introduction in chapter one, an in-depth review of the relevant literature was undertaken in Chapter 2. This was followed by a pilot study described in Chapter 3, which was conducted to investigate the efficacy of the markerless motion system to reliably undertake repeated measures assessments of a dynamic functional task. This involved repeated measures analysis of four pain-free participants undertaking a stand-to-sit/sit-to-stand task, with intra-class correlation coefficient analysis applied to results.

The description of the methodology for the principal study is presented in Chapter 4. The principal study was an observation based analytical prospective single cohort study investigating kinematics and kinematic change over time and as a result of injury during the sub-maximal inside-of-the-foot pass kick. The participants (n = 29) were elite level football players in Singapore, and were progressively separated during the trial as a consequence of experiencing a spinal, pelvic or lower limb injury into two groups, injured and non-injured. Results for the principal study, which includes those from linear and non-linear statistical analysis methods and descriptive analysis of the data, are provided in Chapter 5. Chapter 6 interprets the results from the pilot and principal studies and discusses the relevance of the findings in the context of the aim, objectives and research questions posed at the start of this thesis and in relation to the previous literature. This chapter also identifies potential limitations in the research undertaken and makes recommendations that may be appropriate for future investigations. The thesis concludes in Chapter 7 with an overview of the research outcomes and potential relevance of the study findings to the clinical environment. Supplementary information is provided in the appendices, which follow the references.

Chapter 2 Review of the Literature

2.1

Sports Injury- Epidemiology & Significance

There is an abundance of epidemiological data describing the incidence of injury for a broad range of sports. In football, injury frequencies of 8 to 8.5 injuries per 1000 playing hours have been reported (Ekstrand, 2011, Hawkins, 1999, Hawkins, 2001). In rugby the injury frequency is exceptionally high with up to 91 injuries per 1000 playing hours being reported in rugby union (Brooks, 2005) and 114 injuries per 1000 playing hours in rugby league (Stephensen, 1996). Football and rugby are both contact sports; however it would be wrong to assume that contact is solely responsible for the high incidence of injury as a large proportion of football injuries are non-contact in nature (Hawkins, 2001). In addition, tennis and cricket although potentially high impact, are considered non-contact sports yet both demonstrate notable levels of injury incidence. For example Abrams, Renstrom & Safran (2012) report that injury prevalence in tennis may be as high as 21 per cent, and in cricket an average of 49.1% of A-grade and provincial cricket players in South Africa will suffer an injury during the playing season (Stretch, 1992). Low impact dynamic sports such as golf, rowing and cross-country skiing also exhibit reasonably high levels of injury incidence (Eriksson, 1996, Hickey, 1997, McHardy, 2007).

The literature suggests that injury prevalence is high, but considering the prevalence and severity of re-injury (Brooks, 2005, Finch, 2017) perhaps of greater concern for the sports medicine community should be the high incidence of recurring injuries. Hamilton et al (2011) suggest that subsequent injury i.e. injury that occurs following an index (initial) injury should be categorized as (1) new injury: different location; (2) local injury: same location, different type; and (3) recurrent injury: same location/type. In Rugby subsequent injuries account for up to 18% of all injuries and importantly these recurring injuries are often more severe leading to an average of 27 lost training or playing days compared to 16 lost days from index injuries (Brooks, 2005). In professional football the findings are similar, with subsequent injury rates ranging from 7% to 22% (Ekstrand, 2011, Hawkins, 1999, Hawkins, 2001). In addition, in football there is a direct correlation between subsequent injury and extended periods of missed activity, with missed training and competing periods of 25.1 to 28 days for recurring injury compared with 18 to 19.1 days for index injuries (Ekstrand, 2011, Hawkins, 2001). Swenson et al (2009) carried out an extensive examination of the pattern of recurring injuries experienced by male and female US high school athletes in a number of sports, namely: American football, football, volleyball, basketball, wrestling, baseball, and softball and identified activity dependent subsequent injury recurrence rates of up to 10.5%. The authors also identified that subsequent injuries were more severe, leading to prolonged physical alterations and, importantly, that recurring injuries increased the likelihood of the athlete discontinuing participation in that sport (Swenson, 2009), thus highlighting the potential physical and psychological effects recurring injury may have on the sports participant.

It is apparent that injury and re-injury are common in football; therefore the question must be asked, why do so many injuries occur? Many practitioners working in the sports environment believe that an important element in regards to injury occurrence may be alteration in how an individual moves during the sporting activity. That is, there is a belief that changes in biomechanics may predispose to increased injury risk or that adaptation following injury, even when recovered and pain free, may increase the risk of re-injury (Bahr, 2005, Moseley, 2006)

Therefore it is important, in order to fully understand the mechanisms that may predispose injury or cause adaptation post injury, to first identify what classifies as 'normal' kinematic movement during specific sporting tasks. Which, in the case of this review, is the sub-maximal inside-of-the-foot pass kick.

2.2

Kinematics During the Football Kick

Numerous studies have explored the relationship between kicking kinematics and skill level with many using the generation of maximal ball velocity during the kick as a guideline to measure performance (Fullenkamp, 2015, Kawamoto, 2007, Lees, 1998, Lees, 2009). It is generally accepted and well documented that proximal to distal segmental sequencing of joint angular movements and velocities plays a major role in contributing to performance when kicking (Dörge, 2002, Levanon, 1998, Nunome, 2006a, Shan, 2005). However, no previous literature has been identified that sought to define longitudinal changes in the kinematic movement strategy employed whilst kicking in adults or the relationship between kicking kinematics, injury and pain. The lack of previous investigation is problematic, making it potentially difficult to identify which variables should be analysed when attempting to identify pathologically induced alterations in kicking kinematics. Therefore, the most obvious option is to investigate those kinematic variables that have been identified in the literature as contributing to performance. These variables offer important contributions to the kinematic process and also play a vital role within the kinematic chain during kicking.

Kicking Technique

The vast majority of previous research undertaken that explores kicking in football has focussed on the kinematic properties of maximal power kicking and the in-step kick (Augustus, 2017, De Witt, 2012, Fullenkamp, 2015, Inoue, 2014, Isokawa, 1988, Kellis, 2007, Lees, 2002, Naito, 2010, Naito, 2012, Nunome, 2006b, Shan, 2011, Shan, 2012). Whilst maximum power is important in game situations, the sub-maximal inside-of-the-foot pass kick, which is often sub-maximal to facilitate enhanced precision (Levanon, 1998), is a commonly used and vital technique in football (Reilly, 2000, Yamanaka, 1997). Interestingly, considering its important role in game situations (Reilly, 2000, Yamanaka, 1997) this technique has received much less attention than other techniques during previous investigations of kinematics during kicking in football (Kawamoto, 2007, Levanon, 1998, Opavsky, 1988, Zago, 2014). Whilst general kicking kinematics are discussed below, it is important to note that, although there are many similarities between the maximal instep kick and the sub-maximal inside-of-the-foot pass kick, there are also definite kinematic differences between the two techniques throughout the kicking action (Levanon, 1998, Nunome, 2002).

Kicking Leg

Undoubtedly the region receiving the most attention in the literature in regards to kinematic analysis of the football kick has been the kicking leg. It is generally accepted that kicking foot velocity is correlated to ball velocity (De Witt, 2012, Isokawa, 1988, Levanon, 1998). Following comparison of dominant and non-dominant sides during kicking, the concept that kicking foot velocity is created by proximal to distal sequential motion involving the thigh, knee and shank was proposed (Dörge, 2002). Nunome et al (2006a) further supported this position when comparing dominant to non-dominant kicking and describe power generation during the kick being a result of 'well-coordinated inter-segmental motion'. Therefore it would seem that for successful kicking, segmental coordination is critical (De Witt, 2012).

During the kicking action the kicking leg hip first extends, adducts and externally rotates (Levanon, 1998) and the knee starts to flex (Nunome, 2006a). The pelvis then rotates around the supporting leg to initiate forward movement (Weineck, 1997) the hip flexes (Levanon, 1998, Nunome, 2006a) and abducts (Levanon, 1998) and there is simultaneous knee extension until impact with the ball (Nunome, 2006a). The literature identifies that ball velocity is closely correlated to the foot swing velocity of the kicking leg (Barfield, 1995, Levanon, 1998, Nunome, 2006a). Although the majority of the foot swing velocity during maximal kicking and pass-kicks is generated by the knee moments prior to ball contact (Dörge, 2002, Levanon, 1998, Nunome, 2006a) there is also an important contribution from kicking leg hip linear velocity. Opavsky (1988) measured kicking hip linear velocity and identified its contribution to ball velocity during two different types of kick. This was supported by findings from a subsequent study that also demonstrated the importance of kicking hip linear velocity in generating lower limb angular velocity during the in-step kick (Nunome, 2005). An investigation of the effects on kinematics when undertaking accurate kicks compared to maximal power kicks demonstrated that alterations in hip linear velocity and pelvic, hip and knee ranges of motion allow the player to adapt to the required task (Lees, 2002). This study also demonstrated that adjustments in kinematic strategies are required for optimal kicking function (Lees, 2002).

Support Leg

Kinematic data for the support leg during the kick is limited. On landing of the support foot during the final stride pre-kick, the knee of the supporting leg flexes to between 26 to 42 degrees, this is followed by extension of the knee joint immediately prior to ball contact (Lees, 2009). Inoue et al (2014) suggest that the support leg acts to absorb shock and research has demonstrated that the supporting leg also acts to slow body movement during the kicking action (Kellis, 2004, Orloff, 2008). The slowing of body movement may act to increase stability to aid the kicking action (Lees, 2010) and this enhanced stability may be one explanation for differences in dominant to non-dominant kicking power (Fletcher, 2013). Inoue et al (2014) also propose that extension of the knee joint in the supporting leg prior to ball contact that was initially identified by Lees et al (2009) and subsequently confirmed in their own study (Inoue, 2014) contributes to the generation of power during the kick. This is achieved by inducing linear upward acceleration of the kicking hip, which has been demonstrated to increase the swing speed of the kicking leg (Nunome, 2005) and thus ball velocity (De Witt, 2012, Dörge, 2002, Nunome, 2006a). The combined effect of these movements in the support leg may act to facilitate power transfer across the pelvis and accelerate the kicking leg during the kicking action (Augustus, 2017).

Pelvis

There is considerable pelvic motion during the in-step kick with between 30 to 36 degrees of rotation (Lees, 2002, Lees, 2009, Levanon, 1998). As the kicking foot lifts the pelvis tilts anteriorly between 17 to 25 degrees and obliquely lowers on the kicking side by 28 to 30 degrees. By the time of ball contact the pelvis orientation has changed to between 10 to 20 degrees of posterior pelvic tilt and 10 to 15 degrees of oblique raise on the kicking side (Lees, 2009, Levanon, 1998). This oblique action has the effect of helping to further raise the hip on the kicking leg side and may contribute to kicking leg swing speed (Lees, 2013). Despite the considerable amount of pelvic motion, it has been suggested that the pelvis contributes only a small amount towards the foot speed in both the maximal in-step kick and sub-maximal inside-of-the-foot pass kick (Levanon, 1998). Conversely Lees et al (2009) postulate that increased pelvic rotation occurring before ball strike should positively influence kicking leg dynamics. Specifically, that kinetic energy and thus power may be transferred from the supporting leg through the pelvis via the kinetic chain to increase kicking leg foot speed (Augustus, 2017, Inoue, 2014). There is general consensus that the pelvis rotates and tilts through both an anterior, posterior and oblique axis during different phases of the kick and that the movements and the velocity at which they occur are critical to kicking technique (Augustus, 2017, Inoue, 2014, Lees, 2002, Lees, 2009, Lees, 2013, Levanon, 1998).

Trunk/Spine

Limited investigation of trunk angular range of motion (ROM) during kicking has been undertaken. The literature reports backward lean during the kick of between 3 and 17 degrees (Lees, 2002, Parassas, 1990) and lateral lean of between 3 and 16 degrees (Lees, 2002, Orloff, 2008). However, perhaps of more significance than spinal ROM during the kick is the contribution spinal kinematics may make to the kicking action. In possibly the first full body 3D analysis of the in-step kick and what some may consider a pivotal investigation, Shan & Westerhoff (2005) demonstrated that increases in spinal motion during the kick create what they propose as a 'tension arc'. This tension arc is created by the positioning and then rapid movement of various regions throughout the kinematic chain from the non-kicking side shoulder to the kicking side foot. The authors also highlighted the important role that the spine plays in the formation and transmission of energy as part of the tension arc mechanism and propose that this contributes to the power generated during the kick (Shan, 2005). This proposition was supported by Masuda et al (2005) when they stressed the importance of whole body coordination to optimise strength potential when kicking. Further support for the contribution of the spine to the generation of kicking power is provided by Naito, Fukui & Maruyama (2012). They identified that trunk rotation contributes directly to acceleration of the shank in the kicking leg and that this occurs as an indirect action via combined segmental rotations (Naito, 2012), a kinematic process that is similar to that described previously as 'dynamic coupling' (Zajac, 2002). A subsequent study that was undertaken to compare trunk kinematics between novice and skilled participants during the maximal instep kick identified differences in trunk axial rotation, peak rotational angular velocity and maximal ROM (Fullenkamp, 2015). Although drawn from a small sample the results demonstrated that skilled participants showed notably increased results for all of the kinematic parameters and that this led to the generation of greater ball velocity during the kick (Fullenkamp, 2015). The authors also identified a moderate positive correlation between peak trunk rotational velocity, peak hip flexion velocity and post strike ball velocity (Fullenkamp, 2015). The research by Naito, Fullenkamp and colleagues (2015, 2012) lends further support to the theory of a kinematic coupling effect, with kinetic energy generation within the trunk and transfer of this energy along the kinematic chain to increase kicking power (Shan, 2005) and serves to confirm the importance of spinal kinematics to the kicking action.

Centre of Mass Displacement

Measurements of perturbations to the centre of mass (COM) have been used to assess stability in non-sporting functional tasks (Alamoudi, 2016) and during gait (Lugade, 2011) with increased COM displacement being associated with reduced postural control and stability. However, in football it would seem that increases in COM displacement might be important for functional task completion. Forward displacement of the COM correlates with increased ball velocity when kicking (Chow, 2006, Manolopoulos, 2006) and is a factor that can be improved with specific training (Manolopoulos, 2006).

It is important when discussing COM displacement in respect to its relationship with stability to understand that postural stability and balance are inherently correlated (Pollock, 2000) and require kinematic adjustments, particularly in the spine, for their maintenance (Rietdyk, 1999). For example, postural adjustments have been shown to contribute to the execution of movement during martial art type kicking (Beraud, 1995, Beraud, 1997). In fact changes in COM have previously been employed as a method for assessing balance (Pai, 1998). Football players have been shown to have relatively high degrees of balance in comparison to many other sports participants (Bressel, 2007, Hrysomallis, 2011). Pailliard & Noe (2006b) employed the single leg standing test with a focus on assessment of postural control in football players of different expertise levels with the eyes open and closed. They identified a correlation between increased player expertise and improved postural stability (Paillard, 2006b). A potential link between changes in postural stability, improved balance and increased kicking power has also been identified (Sidaway, 2007). Chew-Bullock et al (2012) identified a positive correlation between improved balance performance and accuracy when kicking with the dominant leg but no correlation between balance (postural control) and velocity, findings that are somewhat incongruous to those from previous investigations (Sidaway, 2007). However, the study undertaken by Chew-Bullock et al (2012) employed a static single leg balance assessment, which they surmise may lack the functional sensitivity to accurately correlate balance performance with kicking velocity and this may explain the difference in assessment results between the studies (Chew-Bullock, 2012, Sidaway, 2007). Some contradiction exists regarding the effects of balance on kicking capacity, specifically in regard to different age groups (Bieć, 2015). However the majority of research suggests that improved balance and increased postural stability is integral to kicking performance (Chew-Bullock, 2012, Sidaway, 2007) and could be one of the criteria used to measure performance and ability (Paillard, 2006b) and is correlated to levels of expertise in football (Paillard, 2006a, Paillard, 2006b). It is clear that COM, balance and postural control are inter-related and may induce kinematic adjustments. Therefore changes in COM may be indicative of alterations in the kinematic strategies employed for completion of functional tasks. This makes assessment of COM relevant and important to any study of spinal kinematic alteration over time or as a response to injury during a kicking task.

Extensive investigation has previously been undertaken to examine the kinematic properties of various regions during kicking in football and this has included examination of how these regions may interact to improve kicking performance (Barfield, 1998, Lees, 2010). However, there has been limited exploration of how changes or adaptations in kinematic inter-segmental interactions may alter the kicking movement strategy and more importantly any relationship this may form with injury.

2.3
The Kinematic Chain

Spinal Kinematics During Movement

Zhao et al (2008) quantified spinal movement when walking using 3D analysis of segmental motion and identified that functional segmental motions of different spinal regions appear to be strongly inter-related. They describe this phenomenon as a 'segmental kinematic coupling effect' and propose that it indicates a synergistic spinal strategy for locomotion (Zhao, 2008). This is important as it suggests multi-region spinal involvement even during a relatively basic functional task such as walking. As we transition from walking to running, spinal and pelvic kinematics adapt to facilitate this change (Saunders, 2005) and acceleration of locomotion leads to increased muscular recruitment in the trunk (Saunders, 2004). In addition to spinal kinematic coupling during walking and running, the body also implements spinal coupling strategies to achieve specific task oriented movements outside the sagittal plane (Preuss, 2010).

The Kinematic Chain & Sport

The kinematic chain was principally discussed by Reuleaux (1876) and refers to 'an assembly of rigid bodies connected by joints to constrain or provide motion'. A more modern and comprehensive interpretation of the kinematic chain especially when discussing its relevance in the sports environment, would be to describe it as a series of inter-related structurally linked body segments that facilitate sequential transfer of energy, force and motion to accomplish goal oriented tasks (Naito, 2010, Naito, 2012, Sciascia, 2012, Shan, 2005, Weber, 2014). From a complex systems perspective the kinematic chain can be viewed as a number of units forming a goal-orientated dynamic mutual relationship (De Rosnay, 1975, Von Bertalanffy, 1969). To achieve a planned task requires coordinated movement between these inter-related segments or regions. This coordination can be defined as the ability for multiple elements to work together to achieve a required goal (Turvey, 1990).

The current literature points towards the role of the trunk and spine in enabling the creation and or transmission of kinetic energy as part of the body's functional kinematic chain during sport (Lees, 2010, Okuda, 2010, Young, 1996). The contribution of spinal kinematics and the kinematic chain is evident in sports that involve throwing, such as pitching in baseball (Chu, 2016, Seroyer, 2010) and during batting and racquet sports (Lintner, 2008, Weber, 2014). In many kicking sports generating increased ball velocity is considered a fundamental part of good performance. Whilst there are other elements that contribute considerably to kicking performance such as: approach angle (Masuda, 2005), pre-kick approach stride pattern and hip and knee velocity (Barfield, 1998, Lees, 2010) certain elements of kicking performance are directly correlated to trunk and spinal kinematics and the kinematic chain (Fullenkamp, 2015, Shan, 2005, Sinclair, 2013). Sinclair et al (2013) demonstrated that sagittal plane torso rotation velocity was correlated to increased ball velocity during the punt kick in rugby league. This is in agreement with Fullenkamp et al (2015) who demonstrated a similar contribution from spinal rotation to the generation of ball velocity during the instep kick. It is also proposed that kinetic energy transfer mechanisms through the kinematic chain play a vital role in the generation of ball velocity during kicking (Naito, 2012). This supports the theory that spinal motion and a congruent kinematic chain is inherent to improved performance and creating power when kicking (Shan, 2005).

Previous research would suggest that an important requirement for successful human movement is that the body can organize the redundant degrees of freedom that exist in the musculoskeletal system (Bernstein, 1967). In addition, the coordinated movement between limbs (inter-limb coupling) or segments (inter-segmental coupling) is an essential aspect of motor behavior (Tepavac, 2001). It is undeniable considering the literature presented that the kinematic chain is vital to optimum sporting task completion therefore, it is also important that an understanding is developed regarding factors that may cause change or adaptation to the function of this chain.

2.4
Movement Adaptation

Spinal Adaptation During Sport

In cricket, it would seem that spinal kinematic movements might be dependent on the technique used. For example, fast bowlers display differing spinal kinematic sequences, with alterations in lumbar ROM and velocity, depending on whether a mixed technique or a side-on/front-on bowling style is employed (Burnett, 1998). Other technique-induced spinal kinematic adaptations have previously been identified during the tennis shot, with tennis players utilising increased spinal rotation during the double-handed backhand shot when compared to the single-handed backhand shot (Kawasaki, 2005). Skill level also seems to impact spinal kinematic movement. Differing spinal kinematic movement patterns have been observed in golf with skilled players demonstrating increased pelvic rotation on follow through compared to less skilled players (Okuda, 2010). Less-skilled tennis players demonstrate increased spinal hyper-extension during the serve when compared to skilled players which may expose less-skilled players to an increased risk of injury due to repeated excessive loading of the spine (Chow, 2009a). Conversely, skilled football players demonstrate increased trunk motion when compared with less skilled players (Shan, 2005). The contrasts in spinal kinematic requirements that are apparent in different sports would suggest kinematic demands vary depending on the sport played and that skill level and technique may also effect how the body adapts spinal kinematics to complete the required sports specific tasks. However, the true extent that different types of sport, skill and technique may have on kinematics is difficult to judge, as the methodology of the discussed research (Burnett, 1998, Chow, 2009a, Kawasaki, 2005, Okuda, 2010, Shan, 2005) varies broadly in respect to the variables assessed, the measurement process and the number of participants examined.

Movement Adaptation Over Time

Limited investigation has been undertaken to directly identify normal kinematic adaptations and changes in movement or variability over time in injury free athletic populations. A study examining bilateral kinematics following anterior cruciate ligament (ACL) injury did identify consistent movement patterns in the lower extremities within an injury free control group over an extended period of time (Goerger, 2015). Bauer & Scholhorn (1997) carried out a longitudinal comparative study of the kinematic movements of two discus throwers over a one-year period. They identified that variation in the participant’s movements was greater between than within assessments, suggestive of changes in kinematic movement strategy over time (Bauer, 1997). In elite rowers it would seem that spinal kinematics do alter over time although whether this change is a result of training or normal time-based adaptive variation is not clear (McGregor, 2007). Following estimation of the coefficient of variation (CV) for repeated instep football kicks, Lees & Rahnama (2013) suggest that there was no significant change in the levels of kinematic variability over time between-assessment sessions but notable within-assessment variability was identified for the variables examined. However, this study (Lees, 2013) compared the mean percentage change from a combination of kinematic and kinetic variables and therefore may not be fully representative of changes in variability that may have occurred over time in individual variables. This is the only study identified that has examined repeated test levels of variability during kicking in football. It is important to note that this study examined only the instep kick (Lees, 2013), therefore the results identified may not directly translate to other types of kick.

Movement Adaptation to Injury & Pain

The factors that may alter the way an individual moves following injury and experiencing pain are complex. A major role of pain is as a protective mechanism (Castana, 2009) and thus the experience of pain following a sports injury may raise anxiety for the athlete and precipitate a fear avoidance movement strategy to be adopted

(Leddy, 1994). Anxiety and the resultant fear avoidance that may follow as a result of injury could in turn have an impact on the athlete's ability to return to optimum sports function (Kvist, 2005, Ross, 2010, Swinkels-Meewisse, 2003). For example, in a systematic review of the literature Ardern et al (2013) identified that lower levels of fear were an important psychological factor that related to a faster return to sport and increased likelihood of the athlete returning to pre-injury performance levels. However, even with improved positive emotions following rehabilitation, fear may still be a prominent factor when the athlete returns to sport (Ardern, 2013). The effect of fear and anxiety may also induce negative effects following recovery from injury and pain. Fear avoidance mechanisms have been shown to reduce lumbar spine and hip velocity and acceleration during reaching tasks in individuals who have recovered from a previous episode of lower back pain (LBP) (Thomas, 2008). This would suggest that kinematic adaptations occur, in this case specifically during target related functional tasks as a result of injury even after full pain free recovery has been attained. The importance of the psychological and emotional contributions to pain is such (Gatchel, 2007, Roditi, 2011) that interventions to address this element of the pain process are now generally accepted as an important conjunct to more traditional therapeutic interventions (Sullivan, 2010, Wilson, 2018).

In addition to psychological distress, injury and pain may also lead to alterations in neural processing that could in some instances cause sensitisation and adaptive changes in the central processing regions of the brain (Plinsinga, 2015, Plinsinga, 2018). This 'neural sensitisation' may induce hypersensitivity to pain (Rio, 2014, van Wilgen, 2011) and affect how the athlete moves their body. For example it has been suggested that it may cause sensory changes bilaterally in unilateral tendinopathy and lead to reduction in reaction times when moving (Heales, 2014). It may also reduce movement variability and increase loading of the spine during certain tasks (van Dieen, 2017) and reduce hip and increase knee ROM during jumping (Sheikhhoseini, 2018) thus altering the normal movement pattern employed. However, it is important to note that the presence of neural sensitisation following injury is not generalisable as it is not universal and may be dependant on the type of injury and the sport played (Piuerto, 2014, Plinsinga, 2018).

The contributing factors that precipitate adaptations in spinal function following injury and pain are not well documented in respect to the sporting environment although an abundance of research has demonstrated the effects of back pain and specifically chronic back pain on spinal kinematics. It is commonly accepted that back pain populations demonstrate alterations in spinal muscle activity. Back pain sufferers may also exhibit reduced deep back muscle activity (Lindgren, 1993) that may reduce spinal stability (Wilke, 1995) and increased superficial muscle activity (Van Dieen, 2003a) that may act as a protective mechanism to reduce spinal movement (Van Dieen, 2003b). Proprioceptive control and proprioceptive variability differences have been identified in back pain populations (Brumagne, 2000, Claeys, 2011, Gill, 1998, Lee, 2010, O'Sullivan, 2003) with back pain sufferers exhibiting reduced proprioceptive control of the spine that could potentially compromise postural stability (Georgy, 2011). A strong relationship between back pain and altered balance and postural spinal control strategies has been demonstrated (Johanson, 2011, Mok, 2011) and there is a significant association between lower back pain and reduced neuromuscular control of the lumbar spinal muscles (Renkawitz, 2006). Pain may also adversely affect the movement strategies that are employed in the lumbar spine during functional tasks. This was demonstrated when altered spinal movement strategies were identified in some chronic back pain sufferers during a lifting task, with higher self-reported pain intensity and severity being correlated with reduced repetitions and more guarded and less smooth lifting patterns (Slaboda, 2008). Kinematic movement and muscle activity adaptations were also demonstrated in a subsequent study investigating biomechanics during lifting, with reduced variability of spinal muscle contractions and reduced ROM of lumbar spinal movement identified in a LBP group (Falla, 2014). Alterations of spinal movement have also been demonstrated in back pain populations in the sports environment during sports specific goal orientated tasks. LBP sufferers exhibited increased spinal flexion, side bend and rotation, and decreased velocity of rotational movement during different phases of the golf swing. From this study it is apparent that golfers suffering from LBP automatically made adjustments in their kinematics in order to complete the required task (Lindsay, 2002). Even a single acute bout of spinal pain may cause immediate changes in individuals that alter their functional kinematic movement strategy (Taylor, 2003). Williams, Haq & Lee (2010) found that experimentally induced acute LBP produced gait-related kinematic changes with ‘automatic attenuation of ROM and reduction in movement velocity’. However, the authors themselves recognised that the effects were not universal and that further research and clarification was needed. The authors also noted that experimentally induced pain might not necessarily be equivalent to clinical pain presentations

(Williams, 2010). An important caveat that must be considered when discussing the existing evidence that has sought to explore changes in lumbar muscle activity, proprioception and spinal kinematics as a result of LBP is that the research studies comparing non-pain participants to LBP populations did so whilst the LBP participants were suffering pain (Brumagne, 2000, Claeys, 2011, Falla, 2014, Gill, 1998, Johanson, 2011, Lee, 2010, Lindgren, 1993, Mok, 2011, O'Sullivan, 2003, Renkawitz, 2006, Slaboda, 2008, Van Dieen, 2003a, Williams, 2010). Therefore it is not clear how transferable the findings would be if the back pain participant's symptoms had been quiescent or if they had experienced full resolution of symptoms prior to testing.

Compensation/Regional Interdependence

'Compensation' and or 'compensatory injury' are common expressions widely used in the clinical environment to describe how alterations in function as a result of injury or pain in one region of the body may impact another region. These terms are employed to describe how the body may adapt its function in an attempt to maintain a state close to normal homeostasis (Bondi, 2005, Zelis 1970). Another term that is often applied in lieu of compensation is 'regional interdependence'. The underlying mechanisms of compensation or regional interdependence are often biomechanical or pathological in nature (Wainner, 2007). A musculoskeletal example of this is the positional and movement changes that can occur in the spine as a response to underlying spinal pathology and deformity. These adaptations ensure the individual is able to maintain a horizontal gaze and stable centre of gravity (Lamartina, 2014). However, it is important to note that functional alterations will most likely involve and may also be driven by neurophysiological and bio-psychosocial elements as well (Chapman, 2008, McEwen, 1998). Understanding the role of regional interdependence in injury epidemiology may be vital (Wainner, 2007) as it could help to direct more efficient diagnostic techniques (Cibulka, 1998) and injury interventions (Muth, 2012, Salom-Moreno, 2014). For example, as previously discussed, spinal injury and pain can adversely impact spinal posture and control (Georgy, 2011, Wilke, 1995). This is important, as there is evidence that altered spinal positioning could have an adverse affect on lower limb kinematics, which may increase lower limb injury risk. Hewett, Torg & Boden (2009) observed the movement and positional characteristics of ACL injury and identified a correlation between increased lateral trunk displacement and increased knee abduction which they suggest increased the stress on the ACL, however these findings were only identified in female athletes. By analysing trunk displacement following a forced release perturbation of the trunk in three directions, Zazulak et al (2007a) demonstrated that ACL injury incidence may increase with trunk and spinal proprioceptive deficits. Barnett et al (2013) suggest that increased trunk flexion during a side-step cutting task will increase the force placed on the ACL and thus increase ACL injury risk. This view is supported by the findings of Sheehan, Sipprell & Boden (2012), who identified increased ACL injury risk with posterior centre of mass displacement relative to the base of support and a smaller trunk angle (reduced trunk flexion) during uncontrolled landing. Conversely, Blackburn & Padua (2008) argue that increasing trunk flexion during controlled landing will reduce ACL injury risk. A possible explanation for the disparity in the findings of these research studies is that the protocol employed by Blackburn & Padua (2008) required controlled landing in the sagittal plane whereas the protocol used by Barnett et al (2013) involved transverse movement of the trunk with increased rotational stress on the hip and knee joints, and the study undertaken by Sheehan, Sipprell & Boden (2012) retrospectively examined uncontrolled landing during competition. Therefore it would seem, considering the findings in these three studies (Barnett, 2013, Blackburn, 2008, Sheehan, 2012) that not only the type and direction of landing but also the trunk position during the task contributes to the optimum body position to reduce the risk of injury to the ACL. More recently Schuermans et al (2017) carried out a prospective study over a one-and-a- half season period to investigate if a correlation existed between running kinematics of the lower limb and spine and the incidence of hamstring injuries in football players. They identified that increased anterior pelvic tilt and thoracic side bend during parts of the gait phase did predispose players to an increased risk of experiencing a hamstring injury (Schuermans, 2017). Considering the literature presented, it is reasonable to assume that any pre-existing condition that alters or affects spinal positioning such as prior injury, may have the effect of increasing the risk of injury in the LEX during certain dynamic tasks. However, whether a pre-existing condition alters spinal positioning during kicking or if this has the effect of increasing injury risk is yet to be clarified.

Previous investigations have sought to explore how injury may affect or alter kinematics and a number of examples of compensation or regional interdependence can be identified in the literature (Kendall, 2010, Stupar, 2010). In a longitudinal study Hofbauer et al (2014) identified kinematic changes over time in the injured and

contralateral lower limb following ACL injury. This finding is supported by a subsequent study (Goerger, 2015) also demonstrating that knee ACL injury alters the kinematics of both lower limbs with the alterations in the uninjured limb being attributed to compensatory mechanisms. Importantly this study has also identified that as a result of these compensatory mechanisms, both lower limbs adopted movement patterns that had previously been linked to increased injury risk (Goerger, 2015). Previous groin pain has been shown to influence hip and pelvis kinematics and also reduce the capacity of the athlete to adapt to different postural positions during a maximal instep-kicking task (Severin, 2017) and patients suffering from patellofemoral pain syndrome demonstrate increased ipsilateral trunk lean during the single leg squat when compared to controls (Nakagawa, 2012). The authors state that it is not clear if the ipsilateral lean is a consequence or causative factor for the injury (Nakagawa, 2012).
Limited research has been undertaken to investigate the potential relationship between biomechanical changes in the pelvis and lower limb and causation of spinal injury and pain. Scholtes, Gornbatto & Van Dillen (2009) identified a correlation between LBP and hip kinematics in participants who played the rotational sports of tennis and racquet ball, with LBP participants demonstrating earlier lumbo-pelvic rotation and increased maximal lumbo-pelvic rotation angles during hip rotational movements. The authors suggest that this spinal kinematic adaptation may increase the risk of lower back injury (Scholtes, 2009). Other investigations have identified an association and correlation between reduced hip mobility and LBP (Ellison, 1990, Mellin, 1988) although the exact nature of the relationship between these two regions was unclear in regards to whether LBP was the cause or a result of hip mobility alterations. Tecco et al (2002) identified increased trunk muscle activation and reduced postural control, which is associated with an increased risk of spinal injury (Oyarzo, 2014, Takala, 2000) in participants who have an existing ACL injury. A singular prospective study also identified that college athletes with acquired ligamentous laxity or overuse injury in the lower limb had an increased risk of developing low back pain (Nadler, 2001), and reduced dorsiflexion of the ankle has been demonstrated to correlate with chronic or intermittent LBP (Brantingham, 2006). However, again it is unclear whether the ankle limitation is a causative factor or an adaptation and compensation to the back pain that is present (Brantingham, 2006).

It is apparent from the literature discussed that the body may compensate for injury, pathology or pain in one region by adjusting the kinematics of other regions. It is also reasonable to postulate, considering the obvious importance of harmonious multi-segmental motion, that alterations in biomechanics within one region of the kinematic chain may lead to increased load and stress on other regions and potentially an increased risk of experiencing injury.

Kinematics - Resolved Injury/Pain

A very important factor to consider when discussing spinal kinematics and any potential relationship to injury and pain is the response of the body following recovery from injury. Hides, Richardson & Jull (1996) previously demonstrated that spinal muscle recovery following acute injury may not be an automatic process. In addition, altered trunk neuromuscular patterns have been identified in participants following recovery from acute LBP (Cholewicki, 2002). The authors of this investigation propose that these alterations may be indicative of the body undertaking an adaptive process as a response to the previous injury (Cholewicki, 2002). This theory is supported by the findings of MacDonald, Moseley & Hodges (2009) who identified changes in spinal muscular control in recurrent back pain patients when the participants were pain free and seemingly functioning normally (MacDonald, 2009). If spinal kinematic adaptations do persist following recovery from injury, it has been suggested that this may place increased stress on the spine (Makalesi, 2011). Reductions in the coordination variability between the pelvis and lumbar spine whilst walking and running have also been identified following recovery from back pain when compared to the pre-injury state (Seay, 2011a, Seay, 2011b). In fact it has been suggested that 'clinicians need to look beyond the resolution of pain when prescribing rehabilitation for low back pain' (Seay, 2011b).

Limited prior investigation has been undertaken to explore potential kinematic adaptations following recovery from injury in players performing a football-kicking task. Navander et al (2013) identified that players who have recovered from a previous hamstring injury take longer for hip follow-through during the maximum in-step kick and the hip flexion moment during both maximum in-step and side-foot kicking.

In a further study, participants with a history of previous hamstring injury demonstrated significant differences between dominant and non-dominant sides for hip flexion/extension moments and knee and ankle joint velocities during the instep kick

(Navandar, 2017). This would suggest that even after recovery from injury and pain there might still be an impact on the kinematic movement strategy employed.

2.5
Movement Variability

A major difficulty that adds to the complex issue of measuring, analysing and comparing human movement in both healthy and pathological states, is that all movement is inherently variable and this variability is present both between and within individuals. The successful completion of a specific goal orientated movement task is an extremely complex and variable neurological and biomechanical process (Chow, 2009b, Martin, 2009) and as such, when we attempt to repeat a movement, there is a level of variability associated with each repetition (Hatze, 1986, Latash, 2012a, Preatoni, 2013). In addition, differentiating the various factors that contribute to movement variability such as measurement error (Preatoni, 2013) and neuromotor processing (Churchland, 2006) is extremely challenging. Martin, Scholz & Schoner (2009) present a useful schematic representation of the complexities surrounding the selection of motor strategies to achieve a goal directed movement (Figure 1).

Stergiou, Harbourne & Cavanaugh (2006) describe human movement variability as ‘the normal variations that occur in motor performance across multiple repetitions of a task’ and it has been argued that variability is a functional necessity in order to facilitate adaptation to the many performance constraints placed on the individual when moving (Davids, 2003). In fact it has been proposed that variability may play an important role in facilitating learning for improved task completion (Wu, 2014). It has also been proposed that movement variability is in part due to a compromise, with the brain aiming to achieve motor behavior that is sufficient for the required task whilst accounting for factors that promote variation (Lisberger, 2015).

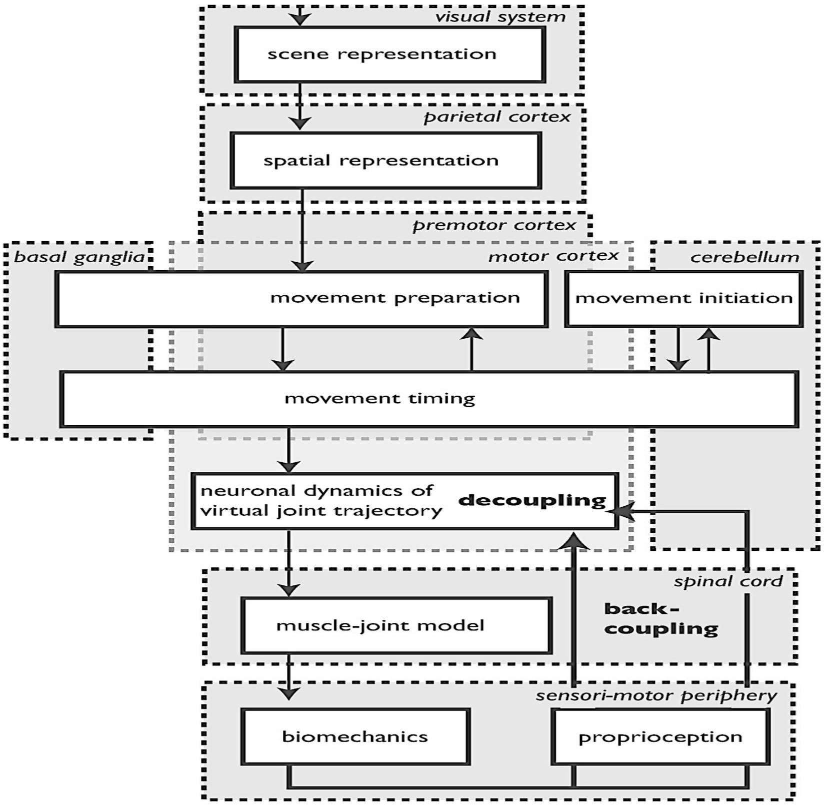

Figure 1: **Redundancy, Self-Motion, and Motor Control** (Martin, Scholz & Schoner 2009)

Investigation has been undertaken to explore the possibility of identifying intra-individual variability in movement patterns during specific tasks. During putting in golf, players exhibit distinct patterns of movement variability to a level that may allow characterisation of individual players (Couceiro, 2013). Similar intra-individual patterns of movement variability have also been identified in race walkers (Donà, 2009) and in basketball free-throw shooting (Schmidt, 2012). Very little research has explored the role of movement variability in regards to kicking in football. Chow et al (2006) investigated player movement variability during the chip kick and identified that skilled players demonstrated reduced COM variability when compared to the less skilled playing group. When assessing maximum in-step kicking, Lees & Rahnama (2013) identified large inter-individual and smaller but still notable intra-individual kinematic variations over time between assessments. Whilst these findings are useful (Chow, 2006, Lees, 2013), it is unclear whether similar levels of variability would be demonstrated during the inside-of-the-foot kicking task or with application of alternate testing procedures.

Movement Variability - Injury & Pain

Investigations in fields other than sports medicine has identified that changes in inter-segmental coordination variability may also be correlated with injury and pain. For example, research has demonstrated that when repetitive tasks are undertaken, experienced operators may adopt increased movement variability patterns compared to less skilled workers and also that the levels of movement variability during certain repetitive tasks may be reduced in some regions with the presence of pain (Madeleine, 2008b). The authors of this particular study propose that the broader movement variability patterns employed by experienced operators may act to reduce the levels of repetitive strain on the tissues and thus reduce the risk of repetitive strain and injury (Madeleine, 2008b). However, the pain experienced by participants in this study (Madeleine, 2008a) was acutely induced via intramuscular injection of hypertonic saline, therefore it is difficult to ascertain if similar findings would be present in more established pain presentations or with intermittent pain. A longitudinal investigation of variability and pain development did indicate that chronicity of pain may affect the levels of variability identified during repetitive tasks (Madeleine, 2008b). Further, it has been identified that variability in spinal muscle activity may be reduced in the presence of a chronic back pain condition (Falla, 2014). In the sports environment, Hamill et al (2005) investigated patellofemoral pain and tibial stress fractures in runners, although not conclusive in regards to cause and effect their findings, are suggestive of a relationship existing between reduced levels of movement variability and increased risk of injury as a result of repetitive strain or trauma. Reduced pelvis-trunk coordination variability was identified in a LBP population and more importantly resolved back pain participants during walking and running, which the authors believe may indicate a reduced ability of the athletes body to respond to perturbations (Seay, 2011a, Seay, 2011b).

The literature suggests that movement variability and segmental coordination variability may play an integral role in how the athlete adapts movement patterns to achieve specific task requirements (Davids, 2003, Müller, 2004). Movement coordination and its variability may be crucial for completion of complex motor tasks during human movement and is an indication of the inherent adaptability within the motor system (Newell, 1985). An example of this is the role coordination variability can play in allowing an individual to compensate for alterations in release timing during some target related throwing sports, (Button, 2003, Nasu, 2014, Robins, 2006).

Evidence is building to support the role that movement variability and coordination variability may play in the body's response to injury and pain (Hamill, 2005, Heiderscheit, 2002, Madeleine, 2008a, Seay, 2011a, Seay, 2011b). In fact, it is possible that changes in variability could predispose an individual to future injury (Brown, 2009, Falla, 2014, Madeleine, 2008a). Much of the previous research investigating the relationship between pain and variability has been undertaken when the research participants were experiencing pain and as such any effects identified should be considered only in this context. Two studies (Seay, 2011a, Seay, 2011b) have provided evidence demonstrating the maintenance of adaptions in variability post pain resolution during walking and running, but further research is required to fully explore these changes during more complex multiplanar functional tasks. Given the potentially important role that variability and coordination variability may play in normal and pathological movement strategies for sporting task completion (Davids, 2003, Müller, 2004) and the need for further exploration of the relationship between pain and variability that has previously been highlighted in this text. It would seem that including analysis of these movement elements is vital to any future research that aims to investigate biomechanical adaptations to injury and pain.

If movement and coordination variability are to be analysed then the challenge is to employ tools that allow us to optimally examine these aspects of movement behaviour (Caballero, 2014). In addition, methods must be employed that allow accurate statistical analysis to be undertaken so that meaningful interpretations can be made from the data that is collected.

Vector Coding

Over recent years, vector coding has gained in popularity as a method of providing data for analysis in respect to inter-segment coordination variability. Vector coding utilises positional signals to create angle-angle plots that represent spatial kinematic motion between segments. It has the capacity to quantify intra-individual movement patterns and variability by measuring the timing and magnitude of segmental motion (Sparrow, 1987). With provision of this data it is possible to produce a value that is representative of the global variability of an inter-segmental coupling relationship drawn from multiple repetitions of a task (Tepavac, 2001). For example, a modified version of vector coding has successfully been employed to test the number of strides required to reliably measure the coordination variability of gait during walking and running (Hafer, 2017). Vector coding has the capacity and sensitivity to identify differences in segment coordination variability when cadence is increased during running (Hafer, 2016) and when comparing injured and non-injured runners suffering from patella pain (Heiderscheit, 2002). Whilst the previous research discussed had identified the benefits of utilising vector coding for movements during gait analysis (Hafer, 2017, Heiderscheit, 2002) a recent study has also identified that vector coding can be utilised to aid in the analysis of inter-segmental movement coordination during the football kick (Li, 2016). Miller et al (2010) when comparing vector coding and relative phase assessment techniques for biomechanical data found both methods effective but vector coding the more useful clinical tool.

Non-linear Statistical Analysis

A number of authors suggest that rather than error, variability is a demonstration of the capacity of the motor system to adapt and may play a vital role in motor control and development (Davids, 2003, Riley, 2002, Seifert, 2013, van Emmerik, 2002). In order to quantify changes in coordinated variability it is vital that appropriate statistical methods are used to extract sufficient meaning from the data. Traditional statistical analysis techniques have employed linear tools to compare the average standard deviations taken from discrete data points during joint movements in order to identify the magnitude of variability (Stergiou, 2011). However, the use of averaging when applying linear tools to explore movement variability makes the identification of temporal patterns impossible (Stergiou, 2006). It has been suggested that better description of temporal patterns may be vital in explaining adaptations in human movement variability that occur as a natural consequence over time (Stergiou, 2004). In recent years in an attempt to better understand the role that movement variability may play, analysis has shifted towards employment of a non-linear dynamic systems approach. This approach moves away from measuring variability by use of the standard deviation or average and focuses on continuous data exploration of the dynamics of movement variability throughout a cycle of movement (Stergiou, 2011). Importantly, applying a non-linear dynamical systems approach allows investigation of the functional role of variability in the sports environment (Davids, 2003). It also facilitates specific analysis of individual goal-directed behaviour (Button, 1999), helps quantify the effect of task specific constraints on individual performance in regard to movement coordination and variability (Davids, 2003), and thus may facilitate in-depth analysis of intra-individual adaptations. A number of different tools fall under the banner of a non-linear dynamical systems approach and may be employed to help analyse movement variability (Caballero, 2014). One of the more recent and potentially useful statistical methods is Statistical Parametric Mapping (SPM). Originally developed primarily for the analysis of functional Magnetic Resonance Imaging (MRI) recordings (Frackowiak, 1997), SPM has more recently been employed as a data analysis tool for biomechanical research (Pataky, 2012). SPM conjoins the general linear model and Gaussian random field theory to analyse spatiotemporal data through statistical parametric maps (Friston, 2003). The maps are created by calculating the scalar output statistic SPM(t) separately at individual time nodes. The SPM(t) calculation identifies the magnitude of differences in the data but is unable in isolation to verify the null hypothesis. To test the null hypothesis a critical threshold is calculated at which only five percent of smooth random curves would be expected to traverse (Friston, 2007). If the SPM(*t)* trajectory crosses the critical threshold at any time node the null hypothesis is rejected. Often, multiple adjacent SPM(*t*) points may exceed the critical threshold and when this occurs these are named “supra-threshold clusters”. Random field theory expectations are then applied regarding the supra-threshold cluster size to facilitate calculation of cluster specific *p*-values (Pataky, 2008a). SPM has previously been employed to analyse three publically available research data sets and demonstrated reduced statistical bias for analysis of 3D knee kinematics and 3D ground reaction forces (Pataky, 2013). SPM has also demonstrated the capacity for providing tight control for type 1 and type 2 errors during analysis of multi-muscle electromyography data (2015) and was also utilised successfully to investigate correlations between walking speed and the distribution of foot peak plantar pressure (Pataky, 2008b). Pataky and colleagues (2013) suggest that SPM is capable of guiding analyses of complex biomechanical systems and asserts certain advantages compared to other statistical methods for analysing data derived from 3D measurement (Pataky, 2012). They propose that SPM facilitates immediate spatiotemporal biomechanical observations of the data whilst reducing the potential for biased assumptions regarding the information collected (Pataky, 2012). However, there is some concern at least when SPM is utilised for brain imaging analysis, that it may be susceptible to high family-wise error rates (Eklund, 2012). There is also the risk that SPM analysis may inflate statistical importance and provide false positives based on spatial properties if distributional assumptions are violated with low cluster thresholds (Eklund, 2015, Flandin, 2017).

2.6
Human Motion Capture

In order to apply the tools previously discussed, for the statistical analysis of movement data including the levels of variability that are present, raw data is required that represents the individual's movement during specific tasks. Provision of this raw data is most commonly achieved by the application of human motion capture techniques.
The study of human movement is not a recent phenomenon. In the 1600s Borelli linked anatomy and mechanics in what is considered by some to be the first biomechanical text (Borelli, 2012). In the late 19th century Marey (1874) and Murbidge (1887) pioneered the incorporation of technology to facilitate improved analysis of human movement by applying photography to record human movements. Since these pioneering days, advancements in technology, particularly in the field of computer science, have led to the development of more advanced and effective systems. Following a review of the evolution of methods for the capture of human movement, Munermann, Coazza & Andriacchi (Mundermann, 2006a) suggest that modern systems are capable of the capture, measurement and analysis of complex patterns of human movement with ever increasing accuracy and repeatability. The authors also propose that since its inception, advances in technological assessment methods to facilitate human movement capture and analysis have in the main 'been motivated by the need for new information on the characteristics of normal and pathological human movement' (2006a). This proposition seems legitimate given the extensive literature on the subject that continues to be produced and the constant advancement and deployment of differing motion capture and analysis techniques and systems in a variety of fields (Cook, 2014a, Mayagoitia, 2002, Owens, 2013, Spielholz, 2001).

It is common practice in the world of elite and professional sport to undertake a myriad of physiological assessments on athletes. These assessments include measurements of: ‘anaerobic capacity, blood lactate thresholds, VO_2max, body composition, agility, strength, power, and perceptual and decision-making capabilities’ (Sport, 2014) and are used to aid characterisation and profiling of the athlete (Reilly, 2009, Wells, 2009) and to ascertain the 'level of preparedness’ to participate (Wells, 2009). Similarly, there has been an increased interest in testing the athlete’s quality of movement and ability to undertake functional specific tasks (Cook, 2014b, Hoog, 2016, Padua, 2009). For example, in football it would seem that functional movement analysis is a tool commonly applied for injury risk assessment (McCall, 2014). It has also been proposed that identification of functional movement changes may facilitate prescription of more appropriate injury preventative exercise regimens (Donate, 2012, Kiesel, 2011). This is not surprising considering that both systemic review and meta-analysis (Hubscher, 2010, Lauersen, 2014, Soomro, 2016) have identified the significant role that specific preventative and or rehabilitative exercise intervention has on reducing the risk of sports injury and the fact that many of these interventions are targeted at improving functional movement and capacity.

Common Motion Capture & Analysis Tools

A major challenge faced by the sports medicine community in respect to human motion capture and analysis is the development of instruments and methods that combine repeatability, accuracy and ease of application. Marker based 3D video motion capture systems have for many years been accepted as the gold standard for assessing human biomechanical movement (Cappozzo, 1983, Ehara, 1995, Ehara, 1997). These systems may provide potentially high levels of measurement accuracy for the assessment of functional tasks (Schache, 2002, Tokuyama, 2005); however they do have some disadvantages. Each assessment requires alignment and configuration of a number of cameras and there is the requirement for specific marker placement on the subject’s skin. Both of these elements can be extremely time consuming and require a certain level of expertise (Gorton, 2009), which potentially make this method impractical in the sports medicine field due to application issues i.e. the time taken for multi athlete assessment (Ceseracciu, 2014). In addition, for repeated tests misplacement of skin markers can affect assessment accuracy (Gorton, 2009, McGinley, 2009) and displacement of the skin relative to the underlying bone during dynamic assessments may adversely affect the accurate tracking of skeletal movement (Tranberg, 1998). Recent years have seen the deployment of a growing number of assessment techniques that attempt to bridge the gap between laboratory based 3D movement capture systems and more clinically orientated assessment protocols that may be faster and easier to apply. Many of these protocols are oriented towards examining the functional capacity of the athlete (Bardenett, 2015, Hoog, 2016, Whatman, 2013). The tests are deployed for basic movement screening (Cook, 2014a) and in some cases are applied as tools as part of injury prediction and prevention programs (Kiesel, 2007, Padua, 2015).

A number of these more clinically orientated screening approaches are applied in the health and sports environment to assess functional movement abilities. One popular method that has received notable attention is 'functional movement screening' FMS™ (Cook, 2014a, Kiesel, 2007). FMS™ is a relatively easy, low cost and effective method for assessing if an individual has 'the essential movements needed to participate in sports activities at a level of minimum competency' (Cook, 2014a). The information collected using the FMS™ is often employed to create a 'movement profile' for the athlete. This movement profile may then be applied to identify changes in movement and symmetry and utilised as part of as an injury prevention protocol (Cook, 2014a). Kiesal et al (2007) found a correlation between a low FMS™ score representative of reduced functional capacity (Cook, 2014a) and increased injury risk in American football players. There is however conflicting evidence for the efficacy of functional movement screening as a reliable injury prediction tool in both the occupational health (McGill, 2015) and sports medicine environments (Bardenett, 2015, Bushman, 2016). Dorrel et al (2015), after review and meta-analysis of the existing literature, found that the FMS™ showed poor sensitivity as a predictive tool for injury and identified methodological and statistical limitations in the existing research as major factors for their findings. Some success has been demonstrated when applying the FMS™ as an injury prediction tool for assessing military personnel (Lisman, 2013). However, efficacy was only tangible when the assessment data was combined with the results from an aerobic fitness test. As aerobic fitness is a fundamental part of military training (Lisman, 2013) these findings may imply that more specificity i.e. making the assessment more functionally applicable to the task required, is needed when implementing injury prediction analysis. In fact, researchers have started to explore the benefits of increased specificity for movement testing (McKeown, 2014). Padua et al

(2009) employed the Landing Error Scoring System (LESS) to assess biomechanics following a specific jump-landing task and propose its benefit for detection of potentially high risk movement patterns on landing. They also identified differences in landing biomechanics between genders suggesting higher risk in the female population for this specific task, which is in keeping with the existing literature (Hewett, 2009, Orloff, 2008, Shan, 2012). However, there is also conflicting evidence regarding the efficacy of this specific functional test. A subsequent longitudinal study refutes the benefits of the LESS for injury prediction (Smith, 2012), whilst a further investigation, although limited to a small sample size, suggested that the LESS assessment might be of benefit as a potential screening tool for predicting ACL injury risk in elite-youth football players (Padua, 2015). Reid et al (2015) assessed the efficacy of a netball specific movement-screening tool (NMST) which demonstrated high levels of inter and intra-assessor correlation for test scoring, but consistency with individual test scores showed low reliability. McCun et al (2016) reviewed the literature in respect of a number of different functional screening approaches; including the LESS, NMST and FMS™ and concluded that none of the functional screening methods presently employed have sufficient evidence to support their use as effective injury prediction tools. Recently the Soccer Injury Movement Screen (SIMS) was introduced as a functional screening tool designed specifically for injury prediction in football. This tool demonstrated good inter and intra-rater reliability but the authors accept that further research is needed to quantify its effectiveness for injury prediction (McCunn, 2017).

Empirical and literary evidence seems to support the proposition that analysis of human movement may often driven by our need to identify and understand underlying pathology (Mundermann, 2006a). Basic functional movement assessments, for example FMS™ are a useful tool for the healthcare and sports environment due to their low cost, ease of application and ability to measure gross functional movement (Cook, 2014a). However, at present it would seem they may lack the necessary accuracy and specificity to be a trustworthy source for identifying potential movement patterns that predispose an individual to injury (McCunn, 2016, Moran, 2016). The search for better specificity has led to the development of functional assessment protocols for more distinct movement patterns associated with particular sports, but to date the evidence is still lacking as to their efficacy as injury prediction tools (McCunn, 2016, Padua, 2015, Reid, 2015). Perhaps the problem is that the observer-based functional tests are not yet specific enough (Fritz, 2001) in respect to the functional movement requirements or characteristics of the individual (Meeuwisse, 1991). For example, many of the functional screening tools highlighted such as the FMS™ employ comparison of bilateral symmetry and or pre-set measurement levels for comparative scoring (Cook, 2014a, Cook, 2014b, McCunn, 2017, Padua, 2009, Reid, 2015). However, many dynamic sports do not require or promote symmetrical movement patterns during functional tasks (Barfield, 1995, Burnett, 1998, Zago, 2014). In addition, it is arguable that a 'normal score', that is a score representing the normal or average population kinematic parameter for a specific task does not exist (Brumagne, 2008, Chow, 2006, Chow, 2009b, Claeys, 2011, Kawasaki, 2005, Latash, 2012b, Okuda, 2010). There is also contention as to the ability of observers to accurately measure and replicate measurements, especially when assessing complex functional tasks. Maclachlanan, White & Reid (2015) undertook a review of the literature that compared movement analysis taken from observer ratings versus three-dimensional analysis of movements during functional screening tasks. The findings suggest that observed analysis of movement lacks accuracy when compared to 3D marker based motion capture systems when assessing dynamic sports specific tasks (Maclachlan, 2015).

Markerless Motion Capture

One possible solution to the problem of combining accuracy, ease of application, and time efficiency may be to employ markerless 3D motion-capture techniques to aid analysis and comparison of movement during specific sports related tasks. Over the last two decades technological advances have progressed to the point where markerless motion capture may be a viable option for human kinematic measurement (Corazza, 2006, Meoeslund, 2001). This method utilises 3D imaging to create a measurable visual-hull representation of the human body which, when combined with the appropriate software algorithms is able to identify joint centres and thus measure biomechanical movement (Corazza, 2006, Corazza, 2007, Mundermann, 2006a, Poppe, 2007).

There is some discussion as to the optimum camera configuration required to attain accurate measurements when using a markerless capture system. Although only limited research has been undertaken, single camera configurations have been utilised successfully to measure certain kinematic movement parameters demonstrating good repeatability (Bonnechère, 2014, Schmitz, 2013). However, other authors propose that multiple camera configurations provide greater accuracy as they reduce the potential for human body self-occlusion (Balan, 2005, Mundermann, 2006a) and therefore, by increasing the number of cameras, it is suggested measurement error can be reduced (Mundermann, 2006a).

Disagreement exists regarding the accuracy of markerless motion capture methods for scientific use. In a comparative analysis of methods for gait analysis, Ceseracciu, Sawacha & Cobelli (2014) reported that kinematic measurement data for movements in the transverse plane attained using markerless motion capture equipment lacked suitable precision for application in the clinical field. In addition, it has been proposed that although markerless clinical gait analysis for the hip and knee joints in the sagittal and frontal planes may be comparable with results obtained from a marker based system, measurement of hip internal/external rotation, knee abduction/adduction and ankle inversion/eversion may be less reliable (Sandau, 2014). There is a potential methodological problem associated with the research undertaken by Ceseracciu, Sawacha & Cobelli (2014) that may explain the poor results obtained as the authors describe self-shadowing being present during data capture as a result of the lighting conditions. Poor lighting leading to self-shadowing has been identified as a variable that may significantly affect the accuracy of markerless motion capture systems (Baak, 2012, Balan, 2005). Contrary to the findings previously highlighted (Ceseracciu, 2014, Sandau, 2014) research has been presented that supports the use of markerless motion systems for research and clinical use. Markerless motion analysis was employed to assess the effect of gait retraining (Mundermann, 2006b). The authors chose a markerless analysis approach to reduce the time requirement for whole body assessment when compared to marker based 3D systems and to allow for natural un-inhibited participant movement (Mundermann, 2006b). The Markerless motion capture system employed was able to identify altered loading of the medial knee compartment when increased medio-lateral trunk movement was present. This exploration of gait retraining demonstrated the potential for using markerless methods to measure human motion to address clinical problems (Mundermann, 2006b). Further exploration of the concept of applying markerless motion capture methods in a clinical context was undertaken when a markerless system was used to quantify hyperkinetic motion in patients suffering from Fragile X Syndrome (O'Keefe, 2014). In this study the markerless system employed was able to measure and quantify kinematic parameters, including accumulative COM displacement and limb movement, and differentiate between control and pathological populations in regards to levels of hyperkinesia. The markerless system employed also demonstrated high correlation with blind-review synchronous video capture methods (O'Keefe, 2014). In addition, markerless motion capture has also been employed to identify alterations in movement patterns during repeated throws of a tennis ball. A markerless system was able to quantify differences in the movements of the elbow, shoulder, trunk and pelvis and also identify reduced variation of joint flexion in the hip, knee and ankle joints when comparing schizophrenia patients to a control group (Sa, 2014). In the sporting environment, markerless motion capture techniques have been employed for assessing upper extremity motion and neuromuscular control during overhand pitching in post operative patients (Chalmers, 2014) and to analyse the kinematics of the shoulder, spine and elbow in tennis players during different types of serve (Abrams, 2014, Sheets, 2011). Markerless motion capture techniques may reduce the errors and preparatory times involved during the data capture process and also the potential for inhibited functional movement that is associated with marker-based measurements (Ceseracciu, 2014, Gorton, 2009, Sheets, 2011). Bartlett (2008) suggests that in order to produce results that are relevant to coaches in real world environments we need to develop more accurate markerless tracking systems. The use of markerless 3D motion capture procedures in the research and clinical environment is still in its infancy and there is some argument as to its application in the research field and also regarding the capacity of markerless systems to accurately measure non-sagittal and rotational movements (Ceseracciu, 2014, Sandau, 2014). In fact in an overview of the use of markerless systems for the tracking of humans in forensic biomechanics, Yang et al identified that all of the markerless systems reviewed had problems with modelling rotational limb movement (Yang, 2014). However, the literature presents some evidence to suggest that markerless motion capture instrumentation can be utilised to provide suitable levels of accuracy for clinical research purposes, depending on the movement parameters that are being examined, for example when movements in the sagittal plane are being analysed (Abrams, 2014, Ceseracciu, 2014, Mundermann, 2006a, O'Keefe, 2014, Sa, 2014, Sandau, 2014, Schmitz, 2013).

2.7
Summary

As previously highlighted sports injuries are a common occurrence (Brooks, 2005, Ekstrand, 2011, Swenson, 2009). However, the possible kinematic mechanisms underlying injury causation and adaptations following injury are often unknown.

The literature informs us that complex integrated spinal kinematic movement patterns are required for locomotion, throwing, kicking and target specific movements and movements of the trunk in different directions (Preuss, 2010, Saunders, 2004, Saunders, 2005, Zhao, 2008). This encompasses most of the elements required to participate in dynamic sports such as football! In addition, evidence is increasing to highlight the vital role the spine plays towards improved performance during some sporting tasks (Okuda, 2010, Shan, 2005).

Overall the literature indicates that kicking performance and generation of power during the kick is a multifaceted process. It requires the coordinated movement of various regions throughout the kinematic chain, constant postural adjustments and the ability of the player to adapt kinematic parameters to task requirements (Nunome, 2006a, Paillard, 2006b, Shan, 2005). A number of factors may influence this process however, of primary concern in the context of this review is the relationship between injury and pain and the kinematic movement strategies that individuals employ, particularly in the spine during a sports specific kicking task.

Bidirectional regional interdependency exists between the spine, pelvis and lower extremity (Blackburn, 2008, Brantingham, 2006, Ellison, 1990, Falla, 2014, Mellin, 1988, Nadler, 2001, Scholtes, 2009, Sheehan, 2012, Zazulak, 2007a). There is growing evidence that highlights the effects of these regional inter-dependent relationships in regards to potential injury risk (Hewett, 2009, Nadler, 1998, Sheehan, 2012). Injury and pain can influence biomechanics and human movement sequencing (Johanson, 2011, Lindsay, 2002, Slaboda, 2008), may have detrimental effects on performance (Hägglund, 2013) and could make the athlete more susceptible to future injury (Hägglund, 2006). In addition, as a result of regional interdependence, injury and pain in a specific region can affect other regions of the body (Wainner, 2007) and these effects may persist even after recovery from injury (Navandar, 2013). When examining injury mechanisms it is vital that we look beyond just localised affects and take account of the relationship that may exist between inter-related regions of the body (Sueki, 2013). This relationship may be fundamental in regards to cause and effect when investigating kinematic adaptations that may result as a response to injury and pain (Wainner, 2007) and must be addressed when considering strategies to predict, prevent and rehabilitate injuries in the sports medicine environment. Unfortunately the normal kinematic adaptations that occur over time during kicking have not been documented and to date there is limited research that has sought to quantify any potential relationship between kicking kinematics, injury and pain. Due to the research previously discussed it is now widely accepted, in the fields of sports science and sports biomechanics, that there is no universal or optimal movement pattern for enhanced performance or completion of goal orientated movement tasks (Bauer, 1997, Brisson, 1996, Button, 2003, Couceiro, 2013, Donà, 2009, Madeleine, 2008b, Morriss, 1997, Müller, 1999, Schmidt, 2012). Therefore, at present it is difficult to ascertain what is 'normal' change in regards to kicking kinematics and what change is induced by or a causative factor for injury. A further complication when attempting to investigate kinematic changes over time or as a result of injury is the inherent movement and coordinated movement variability that is present during any movement task (Preatoni, 2013). Movement strategies for task completion show significant variability both within and between individuals (Chow, 2009b, Latash, 2012b). Kinematic requirements are unique for the individual, vary during different sports and may be influenced by specific task requirements, technique, skill levels and injury (Brumagne, 2008, Burnett, 1998, Chow, 2006, Claeys, 2011, Kawasaki, 2005, Okuda, 2010). In football, there is no 'normal' kinematic movement for completing the same type of kicking task and movement variability is present independent of the type of kick performed (Chow, 2006, Egan, 2007, Lees, 2013).

Given the numerous factors that may influence kinematics it is reasonable to propose that functional assessment of the individual might require utilisation of instruments that can accurately and repeatedly measure human motion during specific and complex tasks. Therefore, methods must be applied that allow measurement of the various regions of interest and assessment of the kinematic relationship between these regions, including statistical quantification of the data that is collected. In the sports environment clinical screening procedures are already employed to assess movement patterns (Cook, 2014a, Padua, 2009, Reid, 2015), however questions arise in regard to the ability of these methods to act as accurate injury prediction tools (McCunn, 2016, Padua, 2009).

A further method that is popular, particularly in sports medicine, is the application of human motion capture. Human motion capture systems such as 3D marker based systems (Tokuyama, 2005) are presently in use that are classed as the gold standard for human motion capture. Yet these systems still remain susceptible to inaccuracy and problems in regard to repeatability and efficiency (Ceseracciu, 2014, Gorton, 2009). One possible solution may be the implementation of new analysis procedures using markerless 3D video motion capture. This may facilitate easy and fast data capture of an individual or team and could provide sufficient accuracy to identify and measure possible kinematic changes during complex functional biomechanical movements (Bartlett, 2005, Sheets, 2011).

The literature presented provides a growing body of evidence to support the importance of congruent multi-regional interconnected movement for completing tasks and that this chain of movement can be adversely effected by injury and pain. However, there are large gaps evident in the knowledge base in regards to how and why these mechanisms actually occur, the level of effect on different regions, and how best to identify and analyse these movements in a manner that will provide real life clinical benefit.
Therefore the aim of this study was to examine changes in kinematic movement patterns over time and as a response to injury in elite level football players during the sub-maximal inside-of-the-foot pass kick by employing a 3D markerless motion capture and analysis system.

Chapter 3 Pilot Study

3.1 Introduction

Markerless camera based motion capture & analysis has previously been used to measure human movement during specific tasks (Abrams, 2014, Mundermann, 2006a, Sa, 2014); however, as previously discussed there is still some debate about its application for human kinematic analysis (Ceseracciu, 2014, Sandau, 2014). In the present pilot research the primary aim was to undertake repeated assessments of complex functional tasks. Therefore, to support the use of the Organic Motion, Open Stage 2 system (Motion) as the primary data collection instrument in the planned principal research study a pilot study was employed to investigate the repeatability of the system for measuring human kinematics. The pilot study assessment consisted of intraindividual repeated kinematic measurements during a stand-to-sit and sit-to-stand (STS/STS) task utilising a test-retest protocol. Sitting and standing as movements are complex functional tasks and are one of the more common actions undertaken during daily living (Schenkman, 1990). The actions of moving from sitting to standing and or standing to sitting have received extensive attention in the previous literature (Bhardwaj, 2016, Culhane, 2005, Kerr, 1997, Kuramatsu, 2012, Reisman, 2002, Schenkman, 1990, Scholz, 2001, Schwenk, 2012, Shum, 2005, Shum, 2007, Yoshioka, 2009). The option to carry out analysis of sit-to-stand only was discarded as the combined STS/STS movement encompasses a more dynamic and functionally challenging task. This action requires the coordinated movement of a number of joints (Schenkman, 1990) and postural adjustments to account for COM displacement and to maintain stability (Kerr, 1997, Kuramatsu, 2012, Roebroeck, 1994, Scholz, 2001). Thus it is a useful movement to employ for analysing and comparing multi joint kinematic actions during a functional task. More importantly from the perspective of assessing the repeatability of pre and post-test comparisons, the mid point of the movement i.e. the point when the sitting action transitions from a sitting motion to a standing motion can be controlled. Control occurs as a result of the participant contacting a chair, stool or other instrument with their bottom during the sitting action, which triggers their return to the standing position. The use of an instrument to standardise the sitting position has been employed in a number of the investigations of the stand-to-sit and or the sit-to-stand task undertaken previously (Reisman, 2002, Scholz, 2001, Shum, 2007). The relative standardisation of this mid point reduces the effects of intra and inter-participant variability with regard to the transition period from sitting to standing, facilitating easier comparative analysis between repeated repetitions of the required task. A further benefit in the context of assessing the repeatability of the chosen instrument is that the previous literature provides information regarding levels of Intraclass Correlation Coefficient (ICC's) that have been achieved previously when assessing the STS/STS task, albeit following the use of alternative measurement tools. This is in contrast to the extremely limited literature regarding ICC scores for repeated assessments during kicking. The ICC is a popular statistical method that helps to provide an indication of the reliability of repeated measurements (Koo, 2016).

Research Question

Is 3D analysis utilising markerless motion capture technology suitable for repeated measures kinematic data collection during a sports specific task?

Aim

To assess the utility and efficacy of employing the chosen markerless 3D motion capture & analysis system as the primary data collection instrument for the proposed principal research study

Objectives

i) Undertake repeated, between session measurements of human kinematic movement variables during a complex functional task.

ii) Analyse the data to assess the reliability of repeated measurements.

3.2
Methods

Null Hypothesis

The null hypothesis for the pilot study was that the Organic Motion, Open Stage 2 system (Motion) would exhibit unacceptable levels of test-retest reliability for between trial data collection for the STS/STS functional task. The null hypothesis would be rejected if ICC (Shrout, 1979) analysis demonstrated good to excellent reliability ICC > 0.9 (Koo, 2016) with a significance p-value of ≤ 0.05 for the between assessment data comparisons.

Research Time Frame

The pilot study was undertaken during a one-week period before starting the first data collection for the principal study.

Location/Climate

The assessment procedures were undertaken at The Osteopathic Centre Pte Ltd clinic, The Arcade, Raffles Place, Singapore. This is an indoor air-conditioned and climatic controlled environment.

Participants

The pilot was an in-house study involving self-experimentation. Four members of the research team (3 males and 1 female (39 +/- 8 years)) undertook the assessment procedure.

Data Collection

Before starting the data recording session participants were required to complete a Numeric Pain Rating Scale assessment (Quality, 1993) (Appendix A) and were allowed to participate in the trial only with a score of 0, which indicates no pain (Hawker, 2011). This questionnaire has proven efficacy for the measurement of pain (Downie, 1978, McCormack, 1988) in cross-cultural environments (Cleeland, 1994). The primary data capture instrument was the Organic Motion, Open Stage 2 (Motion) markerless motion capture & analysis system. The system consists of a proprietary computerised vision processor (Alliance, 2011-2017), 18 digital video cameras (AG, 2017) capable of capture rates of 120 frames per second and arranged in fixed positions (Figure 3) and a screened environment to minimize self-shadowing and reduce the levels of background visual 'noise' (Balan, 2005, Ceseracciu, 2014) (Figure 4). Information from the cameras is fed to a vision processor which, using a proprietary algorithm, forms a three-dimensional hull representation of the body. This three-dimensional hull is then converted into a graphical representation of the participant's body and is used to facilitate tracking of 22 joint centres in real time (Figure 3). The system is then able to track and record the participant's movements whilst they remain within the recording space (Figure 4). Raw data recordings of the joint centre movements for the participants are transferred to The MotionMonitor® Acquisition, Visualization & Biomechanical Analysis Software, Copyright © 2011 Innovative Sports Training, Inc (Innovative Sports Training, 2011). Start and end points for each data recording are programmed into the software to facilitate normalization of the raw data to 100 frames and processing for real-time analysis of biomechanical variables. The data is then exported to Microsoft Excel (2013) for formatting and to facilitate transfer into statistical analysis software (Corp, 2013).

The Organic Motion, Open Stage 2 (Motion) system was switched on and calibrated and the MotionMonitor® (Innovative Sports Training, 2011) software opened. Calibration of the system is achieved by use of a light wand and tool that facilitates the synchronisation of the cameras. The system also auto calibrates to the specific anatomical measurements of the individual participant once they enter the recording space and assume a specific pose.

The assessment protocol consisted of two identical trials, with participants wearing the same tight fitting clothing during both assessments (Ceseracciu, 2014) (Figure 2a). After initial start-up the participants carried out two practice repetitions of the task. Data collection for the first trial was then undertaken with the participants completing five repetitions of a functional task. The functional task consisted of a STS/STS type action. Data recording started from the standing position (Figure 2a & 2b); the participant was required to make contact with the chair (Figure 2a) with their bottom. This was the mid-position of the movement (Figure 2c) and signalled the transition from a standing-to-sitting action to a sitting-to-standing action. Data recording finished when the participant had returned to the upright position (Figure 2a & 2b). To improve repeatability ground markers were used to specify positioning of the participant's feet and the chair position. Participants were required to look forward with an upright posture and flex both shoulders to approximately 90 degrees during the sitting action to help with balance and reduce the likelihood of them sitting fully back into the chair. They were instructed to carry out the STS/STS movement at a steady and constant speed for all recordings.

The software and system was then completely closed down, the system was switched off and then restarted and re-calibrated. Following re-start and calibration, the software was opened and the participant repeated the identical protocol for the second data collection trial.

The following kinematic data was collected for the four participants: ROM for bilateral hip and knee flexion and extension, and lumbar spinal flexion and extension in degrees and COM displacement. The Motion Monitor software (Innovative Sports Training, 2011) utilises Dempster's anthropometric assumptions (Dempster, 1955) to calculate body COM.

Figure 2a

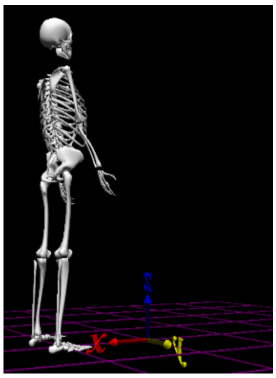

Figure 2b

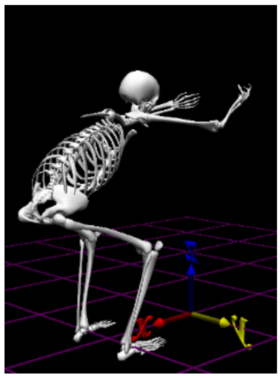

Figure 2c

Figure 2a: **Pilot Study Data Recording Start/End Position/Chair Prop**. Participant start position, clothing and chair used for mid contact point.

Figure 2b: **Pilot Study Data Recording Start/End Position.** Participant start position for data recording.

Figure 2c: **Pilot Study Data Recording Mid Position**. Transition point from sitting to standing.

Graphics produced by The MotionMonitor® Acquisition, Visualization & Biomechanical Analysis Software © (Innovative Sports Training, 2011).

Data Analysis

Recording was undertaken for the full STS/STS task to encourage a fluid movement, however data analysis focussed on the maximum range achieved up to the mid-position of the movement (Figure 2c) when participants contacted the chair and when they were

at maximum hip and knee flexion. The aim of the pilot study was to assess the reliability of the Organic Motion, Open Stage 2 (Motion) system to repeatedly capture human kinematic data during an intra-individual test-retest procedure. To that end ICC analysis of the mean maximum ROM in degrees for the assessed joint variables and mean maximum COM displacement in metres was employed (McGraw, 1996, Shrout, 1979) to facilitate statistical comparison of the data collections for each participant. ICC was chosen because it has been previously employed to assess test-retest reliability of data collection instruments when measuring human kinematic movement (Clare, 2003, Shum, 2005). The literature suggests that ICC values <0.5 are indicative of poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values >0.90 indicate excellent reliability (Koo, 2016, Portney, 2000). These were acceptable standards and were applied as the criterion for the data comparison in the present pilot study.
Statistical significance was recognized if calculation of the ICC level demonstrated a p-value = ≤ 0.05.

3.3
Results

Intraclass Correlation Coefficient

Intraclass Correlation Coefficient (ICC) estimates and their 95% confident intervals were calculated using SPSS statistical package version 24 (SPSS Inc, Chicago, IL) based on a mean rating (3,1)(Shrout, 1979), consistency, 2-way mixed-effects model. All the variables assessed demonstrated test-retest ICC levels above 0.95 at a 95% confidence level with a p-value < 0.01 (Table 1). Based on the standards described previously (Koo, 2016) the Organic Motion, Open Stage 2 system (Motion) demonstrated consistently high ICC test-retest results indicating excellent reliability and repeatability of kinematic measurements and therefore the null hypothesis could be rejected.

Table 1: **ICC levels.** Upper and lower ICC boundaries and p-value significance from the test-retest assessment of the STS/STS for mean ROM during the pilot assessment.

Single Measures	Intraclass Correlation	Lower Bound	Upper Bound	Intraclass Correlation	Lower Bound	Upper Bound	Significant P-value
	Participant 1			**Participant 2**			
Lumbar Flexion	**0.98**	0.97	0.99	**0.96**	0.95	0.97	0.01
Right Hip Flexion	**0.97**	0.95	0.98	**0.98**	0.98	0.99	0.01
Left Hip Flexion	**0.97**	0.95	0.98	**0.98**	0.98	0.99	0.01
Right Knee Flexion	**0.97**	0.96	0.98	**0.9**	0.98	0.99	0.01
Left Knee Flexion	**0.97**	0.96	0.98	**0.98**	0.98	0.99	0.01
COM Displacement	**0.95**	0.92	0.96	**0.97**	0.96	0.98	0.01
	Participant 3			**Participant 4**			
Lumbar Flexion	**0.98**	0.97	0.99	**0.98**	0.98	0.99	0.01
Right Hip Flexion	**0.99**	0.98	0.99	**0.98**	0.98	0.99	0.01
Left Hip Flexion	**0.99**	0.99	0.99	**0.98**	0.98	0.99	0.01
Right Knee Flexion	**0.98**	0.978	0.99	**0.98**	0.97	0.98	0.01
Left Knee Flexion	**0.99**	0.98	0.99	**0.98**	0.97	0.98	0.01
COM Displacement	**0.99**	0.98	0.99	**0.98**	0.97	0.98	0.01

3.4
Summary/ Discussion

The aim of the pilot study was to assess the utility and efficacy of employing the chosen markerless 3D motion analysis system for use as the primary data-gathering instrument in the principal study. More specifically, in order to be appropriate for the planned prospective principal study the system needed to demonstrate high and consistent levels of repeatability for the measurement of kinematic variables when undertaking repeated session recordings. To assess if the Organic Motion, Open Stage 2 (Motion) system could meet these requirements, Intraclass Correlation Coefficient (ICC) scores were calculated to compare the data from the test-retest protocol in the pilot study. ICC was chosen as it has demonstrated accuracy when comparing results in a test-retest scenario for kinematic variables (Clare, 2003, Shum, 2005).

Although the STS/STS movement has been extensively researched, difficulties arise when attempting to identify previous studies that have compared the reliability of measuring this functional task in the same context as the present pilot study. For example, the ICC levels identified in this study were comparable or better than those reported following a systemic review of the test-retest reliability for the STS/STS task

(Silva, 2014). However, the primary aim of the previous systemic review undertaken by Silva et al (2014) was to assess the reliability of clinical tests for assessing neurological disease. Regterschot et al (2014) compared the reliability of a number of test-retest approaches for the STS/STS functional task, with the ICC scores being lower than the present study but the focus for measurement was on generation of peak power and not kinematic ROM as in the present pilot study. A study by Pourahmadi et al (2018) that investigated kinematic values identified ICC levels that were lower than in the present study. Although direct comparisons with the literature were difficult it would seem that the test-retest protocol and equipment employed in the present pilot study were at least as reliable and often more so when compared to previous investigations, certainly for measurements in the sagittal plane. The literature provides guidelines for what ICC values constitute good and excellent levels of reliability in regard to repeatable measurements (Koo, 2016, Portney, 2000). ICC results from this pilot study demonstrated that the chosen markerless 3D motion analysis system (Motion) was capable of excellent test-retest reliability when utilised for measurement of the kinematic variables assessed when a significance level of $p = 0.001$ was applied (Table 1). The present ICC results are also comparable or better than those previously reported during test-retest analysis of STS/STS tasks.

There is a potential problem when using the reliability results from the pilot study as a guideline for efficacy of the proposed measurement system in the main study. That is the potential discrepancy between the level of reliability identified and the actual meaningful change during the movement being analysed. If the meaningful change is less than the reliability or accuracy with which a variable can be measured the results of the study become ineffectual. To combat this problem then the actual meaningful change would need to be known prior to assessment, however this is difficult to measure and has not been identified in the present pilot study or investigated in previous studies of the inside-of-the-foot pass kick.' It is important to bear this in mind when interpreting the results of the main study.

Overall the findings from this pilot study allowed rejection of the null hypothesis and confirmed that the Organic Motion, Open Stage 2 (Motion) system exhibited acceptable levels of test-retest reliability for between trial data collection, for the STS/STS functional task. The pilot study also demonstrated that the system (Motion) was an appropriate tool to be deployed as the primary data collection instrument in the prospective cohort study that had been proposed. However, when considering the findings it is important to note that the present pilot study only investigated kinematic movements that occurred in the sagittal plane. In addition, the pilot study did not identify what level or amount of change could be considered meaningful during the inside-of-the-foot pass kick.

Chapter 4 Methods

4.1 Introduction

The aim of this study was to examine changes in spinal and lower body kinematic movement patterns over time and as a response to injury during a sub maximal inside-of-the-foot pass kick. The methods described in this chapter were applied to address the research questions previously stated.

An observational-based analytical prospective single cohort study was undertaken to investigate kinematic changes in elite standard football players in Singapore. To be eligible for data collection, participants were required to be pain and injury free during the two data recording sessions that were undertaken which were at the start and end of the trial period. The main dependant variables to be examined were lower limb, pelvis and spinal kinematics, and the non-manipulated independent variables were time and participant injury within the trial period. Following the initial assessment procedures the participants were progressively separated during the research period into two groups as a result of injury occurrence, an injured and non-injured group. Participants who did not experience injury during the trial period formed an internal control group to facilitate data comparisons.

Hypotheses

The investigations in this study aimed to accept or reject three null hypotheses. The first null hypothesis was that no kinematic differences would be identified between those participants who experienced an injury during the trial and those who did not. The second null hypothesis was that players would maintain the same kinematic strategies and therefore no significant alterations in kicking kinematics would be identified over the extended period of time between the two assessments. The third null hypothesis was that the kinematic movement strategy would not be altered significantly in the injured players when compared to those players who did not experience an injury. These null hypothesis would be rejected if differences could be identified with a significant level of $p = \leq 0.05$ following data analysis and comparison.

4.2

Protocol

Location/Climate

The assessment procedures were undertaken at The Osteopathic Centre Pte Ltd clinic, The Arcade, Raffles Place, Singapore. This is an indoor air-conditioned and climatic controlled environment.

Inclusion & Exclusion Criteria

All participants were required to complete an informed consent form (Appendix 2), before the initial assessment procedure.

Ethical approval was obtained before commencement of participant recruitment from the Research Ethics Approval Committee for Health (REACH) at the University of Bath.

Inclusion criteria:

- Male
- 16 to 35 years of age
- Elite level football player, national or professional level
- English language skills to a level that enable the participant to understand an explanation of the trial procedures, read and understand the consent form, provide informed consent and follow the necessary instructions to participate in the assessment procedure
- Pain free at the time of all assessments, demonstrated by a score of 0 on the Numerical Pain Intensity Scale (Quality, 1993) (Appendix 1)

Exclusion criteria:

- Unable or unwilling to provide informed consent
- Unable or unwilling to complete follow up assessments
- Recent history (within the last 3 months) of unresolved muscular or skeletal injury severe enough to prevent training or competition
- Diagnosed with chronic spinal pain or any chronic pain condition
- Physically incapable of completing the assessment protocol
- Unable or unwilling to attend the clinic location for assessments

Participant Recruitment

Initial recruitment was aimed at elite level football players in Singapore and included players in the Singapore Premier League (S.League, 2014). Recruitment was undertaken by use of the managerial team as first contact and gatekeepers for access to participants during the research project. Due to withdrawal from the research trial of the two Singapore Premier League clubs that had agreed to allow players to participate, a further round of participant recruitment was required The subsequent recruitment process targeted Singaporean national level footballers with access gained via the Football Association of Singapore (Singapore, 2011)..

Injury classification

To be suitable for injury classification within the research period an injury had to match one of the Orchard Sports Injury Classification System (OSICS) code definitions between 59-119 (Orchard, 2010) and be of sufficient severity that it prevented the player from training or competing for a period of at least 48 hours (Hawkins, 2001). Assessment and diagnosis of the players was the sole responsibility of the relevant squad physiotherapists. The physiotherapists were part of the medical team of the Singapore Football Association National Team (Singapore, 2011) and had the relevant training and experience to identify, diagnose and classify injuries that occurred.

Data Collection

Data collection would be undertaken on a number of occasions. Initial assessments of all participants would provide a baseline (Stergiou, 2005) of kinematic measurement for each participant from which, within and between groups comparisons could be initiated. Further assessments would be undertaken within one week following recovery and being passed fit to play, for any subsequent injuries that were experienced. This would allow for a more complete picture of potential kinematic responses following injury to be attained. At the end of the research period (6 months) a final assessment on all participants would be undertaken. The subsequent and final assessments would provide the opportunity to carry out comparative analysis of kinematic movements over time between assessments. Following the initial assessment and as a consequence of injury incidence, participants were progressively separated into two groups during the research period: an injured and a non-injured group'

Data collection was to be undertaken prior to any physical activity or skills training on that day. Before starting the data recording session participants were required to complete a Numeric Pain Rating Scale assessment (Quality, 1993) (Appendix 1) and were allowed to participate in the trial only if they demonstrated a score of 0, which indicates no pain (Hawker, 2011). This questionnaire has proven efficacy for the measurement of pain (Downie, 1978, McCormack, 1988) in cross-cultural environments (Cleeland, 1994). The primary data capture source was the Organic Motion, Open Stage 2 (Motion) markerless motion capture and analysis system. The system consists of a proprietary computerised vision processor (Alliance, 2011-2017), 18 digital video cameras (AG, 2017) capable of capture rates of 120 frames per second and arranged in fixed positions (Figure 3) and a screened environment to minimize self-shadowing and reduce the levels of background visual 'noise' (Balan, 2005, Ceseracciu, 2014) (Figure 4).

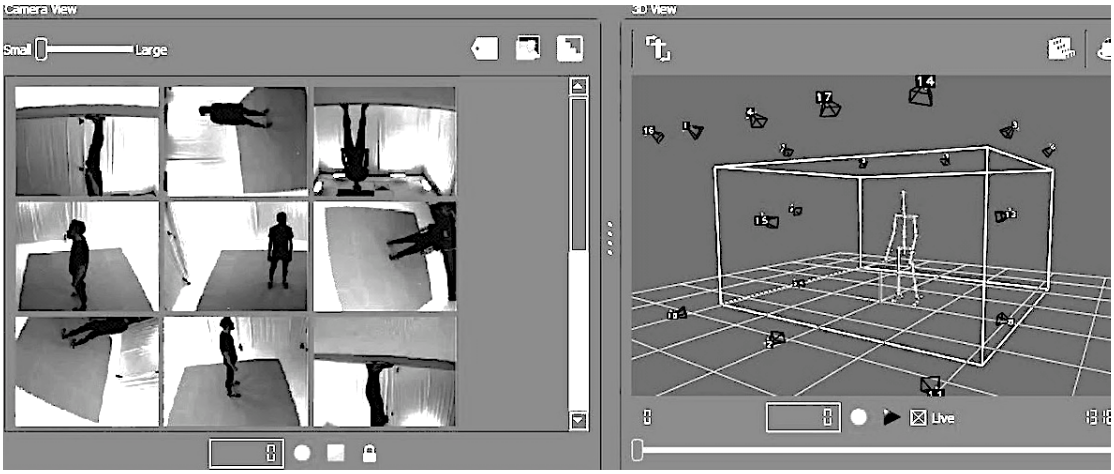

Figure 3: **Recording area and real-time camera view** (left). 3D graphical representation of participant and camera placements (right)

The information from the cameras is fed to a vision processor, which uses a proprietary algorithm to form a three-dimensional hull representation of the body. From this a graphical representation of the participant is formed that is used to facilitate tracking of 22 joint centres in real time (Figure 3).

Figure 4: **Organic Motion Open Stage 2 biomechanical data collection suite** (screened environment)

The system is then able to track and record the participant's movements whilst they remain within the recording space, (Figure 3). The raw data of the joint centre kinematics captured by the system (Motion) is then transferred to The MotionMonitor® Acquisition, Visualization & Biomechanical Analysis Software, Copyright © 2011 Innovative Sports Training, Inc (Innovative Sports Training, 2011). This software facilitates normalisation of the raw data to 100 frames and processing for real-time analysis of a number of biomechanical variables. The data is then exported to Microsoft Excel (2013) to facilitate transfer into statistical analysis software (Corp, 2013).

The functional sports specific task chosen to facilitate data collection and analysis during this research study was the sub-maximal inside-of-the-foot pass kick. This task was chosen, as it is an important and frequently used skill in football (Bloomfield, 2007, Reilly, 2009). The initial assessment protocol was undertaken during the official football season. A secondary follow-up assessment protocol was carried out at the end of the trial period, approximately six months after the first assessment. All assessments were undertaken prior to any physical or skills training being undertaken on the day.

Participants were required to wear the same tight fitting clothing (Ceseracciu, 2014) (Figure 2a) for both assessments. Due to the requirement for the use of mats within the data collection environment football boots were not viable therefore the kicking protocol was undertaken in sock-covered feet. The type of mats employed and the lack of a run up/step up prior to kicking negated the affects of traction loss that could be experienced in non-shod kicking (Anjos dos, 1986). Sterzing, Krolher & Hennig (2008) report potential changes in normal kicking mechanics in trials undertaken in sock covered feet as a result of pain experienced with ball impact during maximal instep kicking. However, this is unlikely to be the case in the current study as a sub-maximal side foot kicking technique was employed and participants reported no pain during the trials. The test area was within the Organic Motion, Open Stage 2 (Motion) environment (Figure 3 & 4). The Organic Motion, Open Stage 2 (Motion) system was switched on and calibrated and the MotionMonitor® (Innovative Sports Training, 2011) software opened. Calibration of the system is achieved by use of a light wand and tool that facilitates the synchronisation of the cameras. The system also auto calibrates to the specific anatomical measurements of the individual participant once they enter the recording space and assume a specific pose.

Following successful completion of the pain questionnaire, participants carried out a supervised warm-up consisting of ten practice kick repetitions without a ball. Once the warm-up was completed the assessment protocol was started. Participants were required to complete a series of repeated sub-maximal pass-kicks. This consisted of a minimum of ten repetitions (Lees, 2013) of the sub-maximal inside-of-the-foot pass kick using a normal competition size 5 stationary football with the dominant leg. Participants were instructed to attempt to be as consistent as possible for both kicking technique and power. The sub-maximal inside-of-the-foot pass kick was chosen due to its relevance to play and its common use in football (Bloomfield, 2007, Reilly, 1983, Reilly, 2000). It also provides a suitable combination of ball speed and accuracy (Lees, 1998) and has received some attention in the literature (Kawamoto, 2007, Levanon, 1998, Opavsky, 1988, Zago, 2014). In order to promote repeatability of the kicking action a number of control elements were implemented to standardise the assessment procedure. No step-up or run-up was allowed for the kick (Lees, 2013) and floor markers were employed for ball and foot placement prior to the start of each kicking repetition (Figure 5). No optimum foot position for this kicking technique has been identified (Lees, 2010) however, Hay (1993) describes 10cm to the side of the ball and 25cm behind the ball as an ideal support foot position during the kick. As the aim was to ensure a standardised initiation point for the kicking action so that the player angle to the ball was approximately 45 degrees (Egan, 2007, Isokawa, 1988) and no step was allowed, it was decided that the support marker would be 10cm behind and 20cm to the side of the ball and the kicking foot marker would be relatively in line with the ball and 25cm behind (Figure 5).

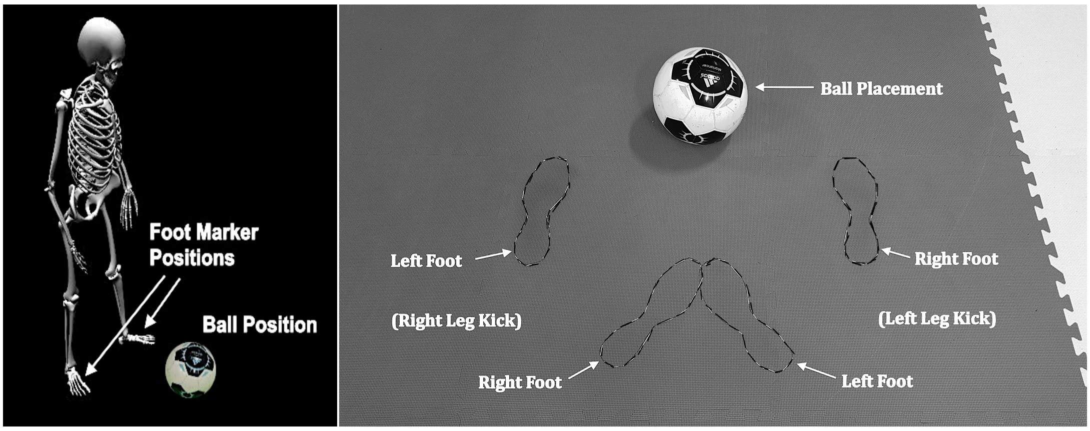

Figure 5: **Data Recording Foot & Ball Marker Positions.** Ball & Foot Placement markers and starting position for each kick repetition.

For each repetition the participant was required to kick the ball at a predefined target, formed by a mini goal, that measured 0.6 x 0.6 metres square and positioned three metres from the ball with the centre of the target aligned facing the ball. Participants were instructed to kick with enough power to achieve a five-metre pass which is within the boundary of classification as a short pass (Hughes, 1987) and to be as consistent as possible with the power of the kick. Failure to hit the target resulted in exclusion of that repetition from the data collection and required a further repetition to be undertaken. The assessment protocol ended when the participant had completed ten successful repetitions of the task with their normal dominant kicking leg. Results from the initial participant assessments were used to create the baseline scores for both group and individual analysis and comparison and an individualised 'functional movement profile' (FMP) for each participant. The FMP was then utilised to facilitate intra-individual between trial comparative analysis using data from both data collection assessments carried out at the start and end of the research study. This approach was deemed suitable as intra-individual based assessment can provide useful insights regarding individual behaviours (Bates, 2004) and may be more accurate than inter-individual assessment for identification of movement patterns during sports specific tasks (Tokuyama, 2005).

Start-End Point

Barfield (1998) breaks the football kick into six distinct stages as follows: (1) approach angle, (2) plant foot forces, (3) swing limb loading, (4) flexion at the hip and extension at the knee, (5) foot contact with the ball, and (6) follow-through. These stages were used to help identify appropriate start and end points for data collection. However, it is to be noted that this investigation employed restrictions of certain kicking parameters that may be considered an integral part of a full and normal kicking movement (Barfield, 1998). This included the kick being initiated from a predetermined position with both feet in ground contact and no step-up prior to the kick being allowed in order to reduce the variation that may be associated with run up and approach angle (Lees, 1998). Due to these imposed restrictions maximum hip extension during swing limb loading, stage 3, (Barfield, 1998) was chosen as the data collection start point.. It is also to be noted that some of the trial repetitions produced minimal or no relative backswing of the kicking leg and the kicking leg hip joint did not move into an extended position beyond neutral. Therefore the start of data capture in these instances occurred from a partially flexed hip position, which was the relative maximum range of hip extension that was achieved. Previous research has used kicking leg lift-off to ball contact as the respective start and end points for the data collection cycle (Fullenkamp, 2015, Masuda, 2005, Nunome, 2006a) most likely as a result of the emphasis being placed on generation of ball velocity (De Witt, 2012, Kawamoto, 2007). However, in football coaching, players are trained to 'kick through the ball' often termed the 'follow through'. Numone et al (2006b) highlight the important role of segmental motion after ball contact and argue that the 'follow through' acts to increase ball contact time. It has previously been suggested that increased ball contact time may contribute to ball velocity (Tsaousidis, 1996) and importantly that it facilitates eccentric deceleration of the kinetic chain and dissipation of kinetic energy possibly reducing the risk of injury (Barfield, 1998). As both concentric and eccentric forces are of importance to formation of the tension arc and are a vital part of the football kick (Shan, 2005), it was deemed necessary to capture kinematic data to the end of the dynamic phase of the kick, stage 6 (Barfield, 1998). Therefore full kicking leg hip flexion at the end of the follow-through was used as the end point for data capture.

*Variables Asse*ssed

To facilitate global movement analysis during the kicking task a total of 19 single joint/COM and 10-coupled joint kinematic variables were measured.
The following variables were measured during the data collection process:

Kicking Leg

The kicking leg is most commonly examined in research of kinematics during the football kick, this is most likely due to the important role it plays in generation of ball velocity during the kick (De Witt, 2012). Importantly, the kicking leg is vital for proximal to distal transmission of energy through the kinematic chain during kicking. Therefore measurement of the kicking hip and knee extension and flexion maximum and full ROM and hip and foot linear velocity was undertaken.

Supporting Leg

As previously reported, research regarding the supporting leg during kicking is scarce but the prior investigations do indicate that support knee kinematics make an important contribution to the kicking action (Inoue, 2014, Lees, 2009, Nunome, 2005). Therefore analysis for the supporting leg was focused on the knee and included: extension and flexion maximum and full ROM in degrees.

Pelvis

Pelvic kinematics play an important role in the kicking action and are essential for transmission of force through the kinematic chain (Augustus, 2017, Lees, 2013, Levanon, 1998). Therefore measurement of maximum and full pelvic side bend, pelvic rotation and pelvic rotational angular velocity was undertaken.

Trunk/Spine

It is reasonable to propose that angular changes in spinal kinematics may be important, as angular changes in spinal position may be indicative of COM displacement (Alamoudi, 2016, Baird, 2009). COM displacement may lead to alterations in balance (Pai, 1998), postural control and stability (Alamoudi, 2016, Lugade, 2011) which, in turn may increase the risk of future injury (Mohammadi, 2012, Paterno, 2010). Therefore, maximum and full ROM for lumbar and thoracic spinal flexion, extension, lateral flexion and rotation were measured. In addition to the possible effects that spinal displacement may have on the position of the COM, trunk rotation also plays an important role in the transfer of forces through the kinematic chain and is correlated to foot velocity, and as such is intrinsic for good kicking technique (Fullenkamp, 2015, Naito, 2010, Shan, 2005). To that end lumbar and thoracic rotational angular velocity were also measured.

COM Displacement

Alterations in COM displacement during certain functional tasks may increase injury risk (Ali, 2014, Blackburn, 2008) and may affect control of balance (Pai, 1998). To assess variations in COM, maximum and the full ROM of COM displacement was measured, using Dempsters' anthropometric assumptions (Dempster, 1955) to calculate body COM.

Variability of Discrete & Coupled Angle Variables

Alteration in joint coordination variability has been identified as a potential risk factor for increased injury (Hamill, 2012, Heiderscheit, 2002, Seay, 2011a). Coordination profiling has been suggested as one method to assess coupled angle variability during functional tasks (Davids, 2003). Therefore a number of coupled angle variables were assessed to explore intersegment coordination variability. To facilitate comparison of group mean and individual coordination variability the vector coding method was applied to the data. Vector coding (Heiderscheit, 2002, Tepavac, 2001) utilises positional signals to create angle-angle plots that represent spatial kinematic motion between joint segments, often referred to as a coupling angle. The standard deviation of the mean angle from each time point is then calculated by employing circular statistics to in order to quantify the levels of coordinated joint variability that are present (Needham, 2014). The coupling angle variable combinations utilised for comparative analysis in this study were chosen because the regions they represent have been shown to contribute significantly to the kinematic chain during the kicking process (Shan, 2005) and included: hip flexion-lumbar spine rotation, pelvic side bend-lumbar spine rotation, support knee flexion-pelvic side bend, hip flexion-pelvic rotation, knee flexion-thoracic rotation, hip flexion-thoracic lateral flexion, hip flexion-thoracic rotation, pelvic rotation-thoracic-rotation, hip flexion-lumbar spine flexion and pelvic side bend-thoracic rotation. In addition to coordinated joint variability, assessment was undertaken to assess levels of group mean and individual variability for discrete (single joint & COM) variables, utilising descriptive examination of the Mean Absolute Deviation (MAD) data.

During the data collection process measurement centred on three main parameters:
i) Mean maximum ROM scores (maximum) for single joint angles, COM displacement, joint angular velocity in the spine and joint linear velocity of the kicking hip and foot.
ii) Mean full ROM scores for single joint, COM and coupled angles.
iii) Movement variability for single joint variables, COM displacement and coupled angle coordination.

A table of the abbreviations used in the results section is provided (Table 3)

Table 2: **Abbreviations used in the results section**

Max	Maximum Range of Motion	**ROM**	Range of Motion
Full	Full Range of Motion	**LumFLex**	Lumbar Flexion
AngVelMax	Maximum Angular Velocity	**LumLatFlex**	Lumbar Lateral Flexion
Vel Max	Maximum Linear Velocity	**LumRot**	Lumbar Rotation
COM Disp	Centre of Mass Displacement combined axis	**PelRot**	Pelvic Rotation
COM X	Centre of Mass displacement Sagittal Plane	**KickHipFlex**	Kicking Hip Flexion
Thor Flex	Thoracic Flexion	**KickHipAbd**	Kicking Hip Abduction
ThorLatFlex	Thoracic Lateral Flexion	**KickKneeFlex**	Kicking Knee Flexion
FMP	Functional Movement Profile	**SupKneeFlex**	Support Knee Flexion
MAD	Mean Absolute Deviation	**ThorRot**	Thoracic Rotation
MAD_{es}	Mean Absolute Deviation effect size	**COM**	Centre Of Mass
$iMAD_{es}$	Independent (between) groups effect size	**SD**	Standard Deviation
dMAD	Dependent (within) group and individual effect size	**SPM**	Statistical Parametric Mapping
MAD1.MAD2	MAD for assessments 1 & 2 respectively	**ANOVA**	Analysis of Variance

Statistical Analysis

Data analysis was focussed on exploring three main areas of interest, namely: injury prediction, normal kinematic changes over time and kinematic change as a result of injury that may be maintained after return to play. For injury prediction a comparison of the between group scores from the first assessment was needed. Assessment of the kinematic changes over time and or as a response to injury required comparison of the within group between assessment data and the between group results from both assessments. When significant changes over time were identified in the injured group, the potential effect of time between the injury and the second assessment was examined. Significance levels for the present study for all data analysis were set at $\alpha = 0.05$. To explore the potential for identifying injury predictive relationships from the kinematic and injury data, binary logistic regression analysis was carried on the first assessment data (single joint, COM & coupled angle variability), with post hoc power analysis utilising G*Power (Faul, 2007). To examine kinematic differences (single joint, COM & coupling angles) between groups and over time, analysis of variance (mixed ANOVA) was undertaken. Where significant interactions were identified, simple effects analysis post-hoc tests were employed to explore pairwise relationships in the data. Where differences were identified over time, specifically changes in kinematics between assessments in the injured group, linear regression analysis was undertaken.

Non-Linear Statistical Methods

Using Statistical Parametric Mapping (SPM) analysis, between group and over time comparisons of the kinematic data (single joint, COM and coupling angle variability) were carried out for the entire period of the kick (rather than discrete values). This was achieved using two-tailed t-tests.

Mean Absolute Deviation & Effect size

The following formulae were employed to facilitate calculation of variation from the mean and the effect size:

To compare levels of group and individual movement variability, MAD scores were calculated from the maximum and full ROM kinematic data (single joint & COM). MAD is a measurement of absolute dispersion of data points from the mean and thus provides important information regarding individual and group movement variability during the task (Gorard, 2005).

$$MAD = \frac{\Sigma|x - \mu|}{N}$$

(F1)

Mean Absolute Deviation (MAD): Where Σ = The absolute sum of each value minus the mean and N = the total number of values.

Mean Absolute Deviation effect size was utilised to facilitate descriptive comparisons of the data. For changes in kinematics between groups independent Mean Absolute Deviation effect size ($iMAD_{es}$) scores were calculated. This was achieved by calculating the difference between mean scores and dividing this score by the pooled MAD of both means.

$$\text{iMADes} = \frac{M1 - M2}{MADpooled}$$

(F2)

Between group (independent variable) Mean Absolute Deviation effect size ($iMAD_{es}$): Where M1 and M2 are the sample means of groups 1 and 2 respectively and MAD_{pooled} is the combined MAD from both groups.

To compare within group and intra-individual change over time, dependent Mean Absolute effect sizes were calculated ($_{d}MAD_{es}$). This was achieved by dividing the difference in mean scores by the MAD of the first assessment, this allowed offset of the effect of correlation between the values (Olive, 2005).

$$\text{dMADes} = \frac{M1 - M2}{MAD1}$$

(F3)

Within group or individual (dependent variable) Mean Absolute Deviation effect size ($_{d}MAD_{es}$): Where M1 and M2 are the sample means of groups 1 and 2 respectively and MAD1 is the MAD from the first assessment.

The MAD_{es} uses a similar formula to Cohens d (Cohen, 1988) but utilises the MAD rather than the standard deviation (SD) (Gorard, 2015). The effect size provides an indication of the levels of change between group scores (Durlak, 2009) or change within groups or individuals between assessments (Olive, 2005). It is an important way of identifying and describing the size of change in movement that is employed to complete sporting tasks (Knudson, 2009).

It is a reasonable argument that the standard deviation would provide similar benefits for comparison of kinematic variability as both SD and MAD provide indications of dispersion from the mean and therefore the variability present during the movement.

However, the MAD holds some advantages in regard to data presentation for the proposed study and specifically the FMPs. It is more realistic and perhaps easier to interpret in real world environments (Gorard, 2015) and is more efficient in real life scenarios where observation and measurement errors may occur (Huber, 1981). It is also more suited for analysisng non-normally distributed data (Gorard, 2005, Stigler, 1973). Importantly, in respect to creation of individual FMPs, calculating MAD_{es} allows the data to be presented in a manner that facilitates user-friendly comparison and interpretation that is applicable for any number of variables irrespective of the original unit of measurement. Graphing of the data to aid visualisation of inter and intra-individual variability across a number of variables also provides insight into extreme data values that could affect the estimations of movement variability when undertaking group comparisons and facilitates more robust case specific analysis (König, 2016).

Chapter 5 Results

Participant Recruitment

A total of 22 participants that were initially recruited did not participate in an initial assessment. These participants were withdrawn from the study by their team management the day prior to the start of their allotted data collection due to time restraints. A further 22 participants underwent the first assessment procedure but were subsequently withdrawn from the study within two weeks of this assessment by their management team due to time restraints.

Subsequently, utilising population purposive sampling, a further 29 participants were recruited and completed both assessment procedures. The participants (n = 29) were elite standard football players who were playing at national level for Singapore in their respective age groups and who met the research criteria. Participants were male, age 18 ± 2, and height 1.65 m ± 0.14 and weight 63 kg ± 12 and made up of a variety of ethnicities.

Participant Epidemiology

Of the 29 participants that completed the study n = 15 (51.7%) suffered at least one injury that was classifiable for inclusion in the trial. Of the n = 15 participants that suffered an injury during the trial period, n = 9 (60%) experienced at least one subsequent injury. The total number of participant days lost to injury during the research study was 265 ($\bar{x}$ = 8.5 ± 8.9). Rates for injury and subsequent injuries were higher than previously identified in the literature (Hawkins, 2001). Subsequent injuries led to a mean loss of training/competition time of $\bar{x}$ = 13.1 days compared to $\bar{x}$ = 7.1 days lost for the initial injury. Of the 18 subsequent injuries experienced by the participants during the research period, five were recurring injuries to the same region, leading to a mean loss of $\bar{x}$ = 8.4 days of training/competition time compared to $\bar{x}$ = 2.8 days lost due to the initial injury (See table, Appendix F).

Global Kinematics During the sub-maximal Inside-of-the-Foot Pass Kick

In general the participants demonstrated a high level of accuracy during the trial procedure with little requirement to undertake more than the minimum of 10 kicking repetitions that were needed ($\bar{x}$ = 10.4) to complete the data collection trial.

A general overview of the mean kinematic results from both assessments for the single joint and COM variables assessed is presented for all participants (n = 29) (Figure 6). This gives an indication of the mean regional kinematic requirements during the task. In addition, the spatiotemporal inter-relationships for a selection of variables that are representative of regional movement throughout the kinematic chain are presented (Figure 7). Results have been separated into four phases each comprising 25 percent of the movement recording to facilitate easier interpretation and comparison of movement parameters between regions. Except for lumbar lateral flexion, larger mean full ROM is demonstrated in the non-injured group for all the variables presented. Conversely, greater mean maximum velocity is demonstrated in the injured group for all of the variables presented.

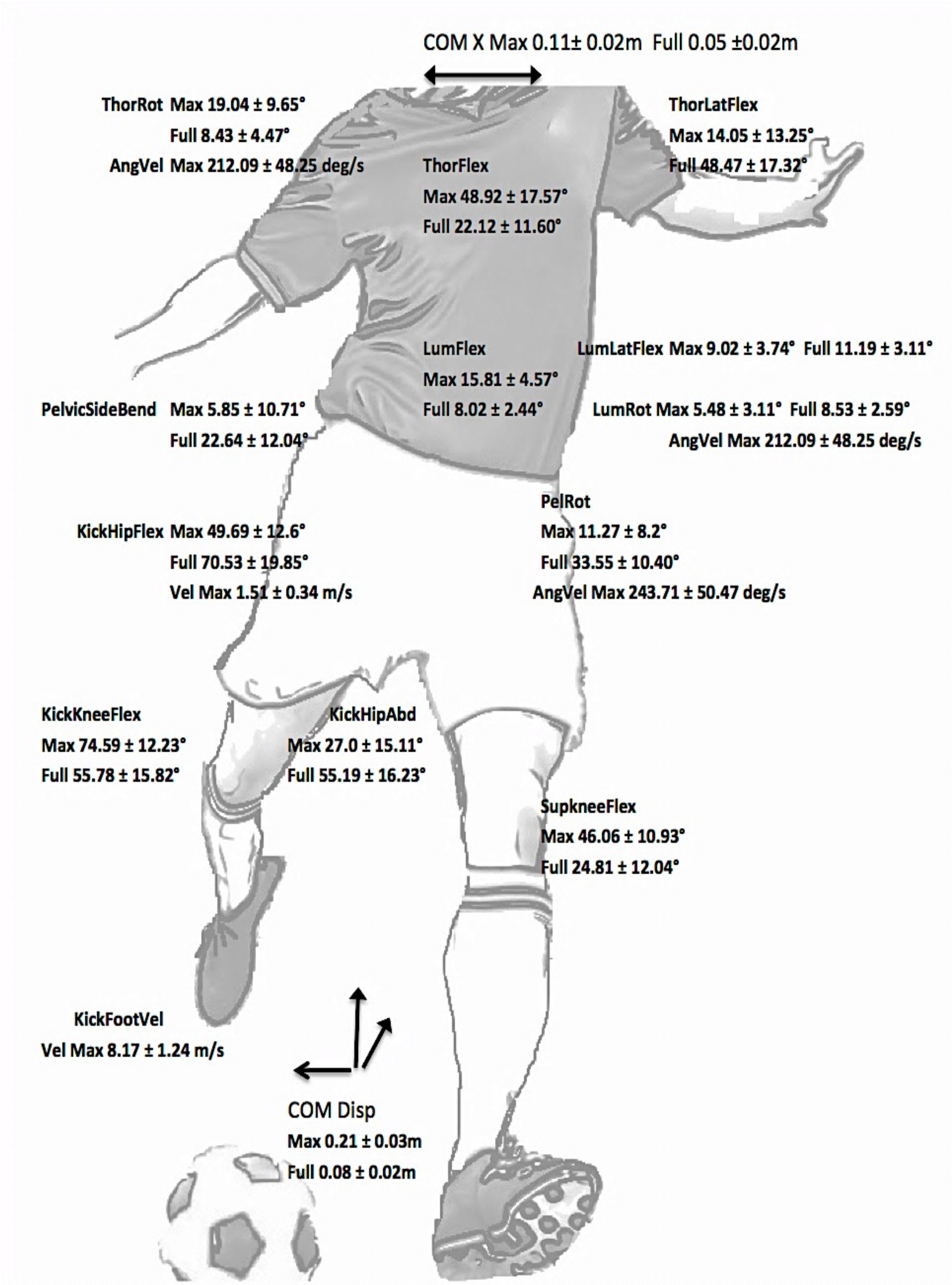

Figure 6: **Combined Measurement Results All Variables**. Combined mean and SD of both assessments for all participants (n = 29) representing the variable scores (single joint and COM displacement).

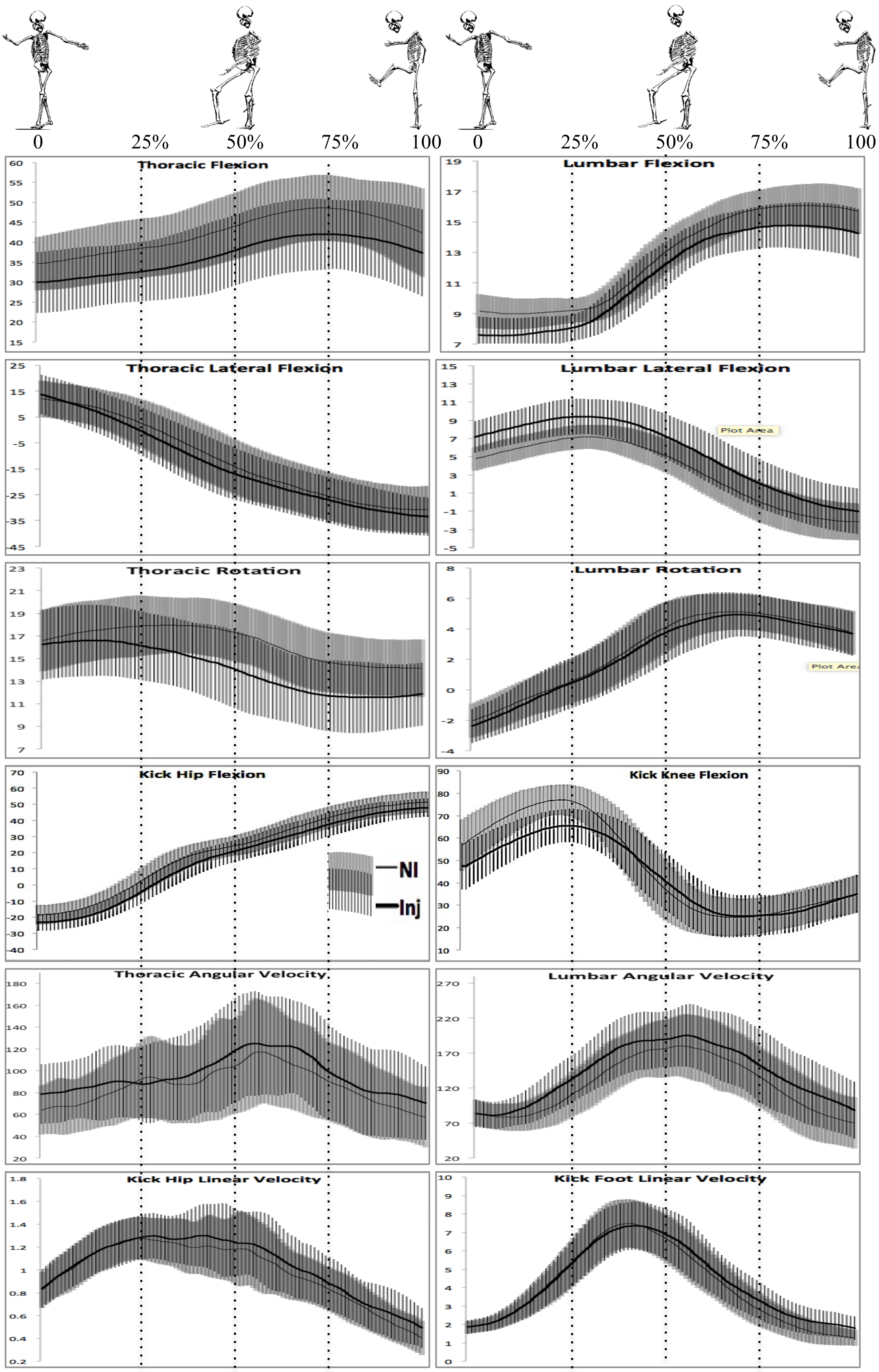

Figure 7: **Full ROM, angular and linear velocity and standard deviations for spinal and lower limb variables.** The mean data from both assessments of the kicking task, for non-injured (NI) and injured (Inj) participants.

Injury Prediction

As previously highlighted the initial assessment provided a baseline measurement (Stergiou, 2005) of participant kinematics. It also allowed exploration of between group differences at the start of the research period and if a predictive relationship might be discernable as a result of any differences identified.

In respect to the first assessment data and identification of kinematic variables that may have injury predictive qualities, logistic regression identified two variables, thoracic flexion maximum ROM (p = 0.030) and support knee flexion-pelvic side bend coupled angle variability (p = 0.043), that may meet this criterion (Table 4). However, it is important to note that these significant findings were identified when logistic regression was applied to analyse individual variables separately. When all of the variables were grouped together for analysis, no significant findings for logistic regression were identified.

Table 3: Logistic regression results: analysis of the first assessment data. Significant findings were identified that may indicate a predictive relationship between these two variables and injury.

		95% CI for odds ratio		
	B (SE)	**Lower**	**Odds Ratio**	**Upper**
Included				
Constant	2.23 (1.12)			
Thoracic Flexion	-0.25* (0.11)	0.63	0.78	0.98
R^2 = .15 (Hosmer & Lemeshow) .19 (Cox & Snell R Square) .25 (Nagelkerke R Square) *p = 0.030				
Constant	3.72 (1.87)			
Support Knee flexion-Pelvic side bend variability	-0.11* (0.05)	0.81	0.90	0.98
R^2 = .13 (Hosmer & Lemeshow) .16 (Cox & Snell R Square) .22 (Nagelkerke R Square) *p = 0.043				

Due to the relatively small number of participants (n = 29) post hoc power analysis was undertaken. It was identified that caution should be applied when interpreting the results from the logistical regression due to low statistical power (z = 1.96, power = 0.13) (Faul, 2007).

Kinematic Change

Mixed within and between group analysis of variance (mixed ANOVA) was conducted to assess the effect of injury (group) on a number of kinematic variables (single joint, COM & coupled angle variability) over time (between first and second assessments).

A significant main effect was identified for kicking hip maximum linear velocity, with players demonstrating lower velocity in the second assessment, F (1, 27) = 12.61, p = 0.001 (Figure 8).

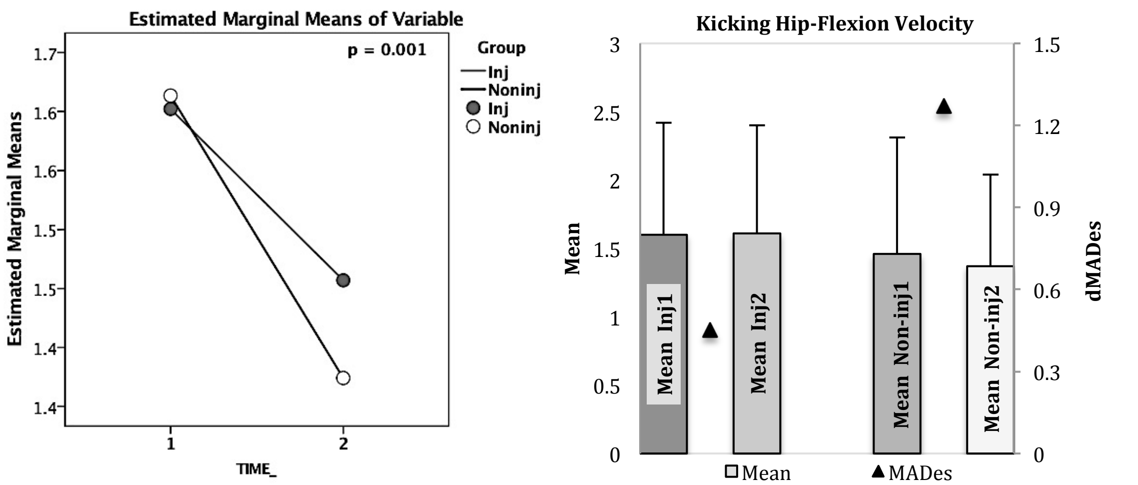

Figure 8: **Kicking hip maximum velocity (ANOVA)**. Mixed ANOVA results significant main effect of time. Group mean, MAD and within group between assessments dMADes.

A significant main effect was identified for kicking foot maximum linear velocity, with players demonstrating lower velocity in the second assessment, F (1, 27) = 15.77, p = 0.001 (Figure 9).

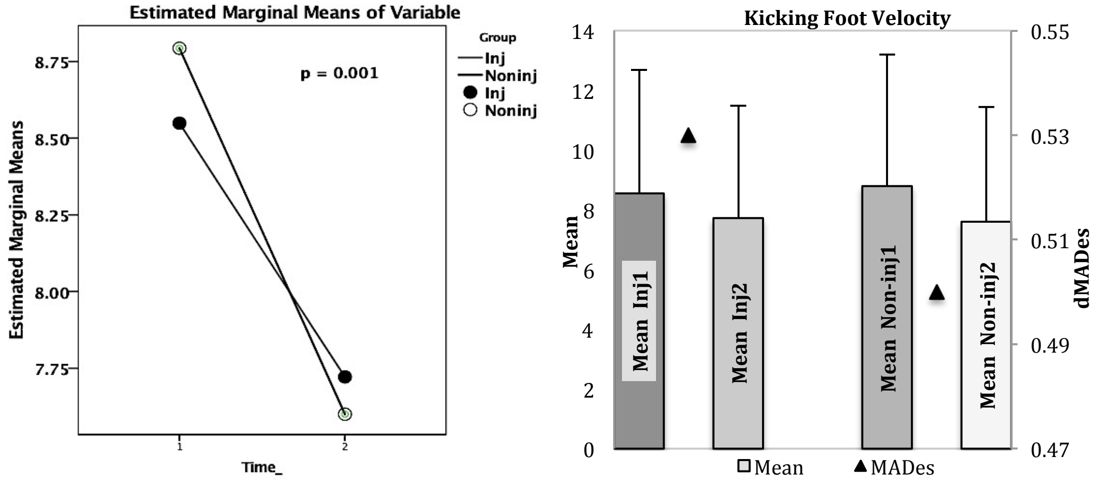

Figure 9: **Kicking foot maximum velocity (ANOVA)**. Mixed ANOVA results significant main effect of time. Group mean, MAD and within group between assessments dMADes.

A significant main effect was identified for kicking knee flexion full ROM, with the non-injured group demonstrating greater movement, $F\ (1, 27) = 4.89$, $p = 0.036$ (Figure 10).

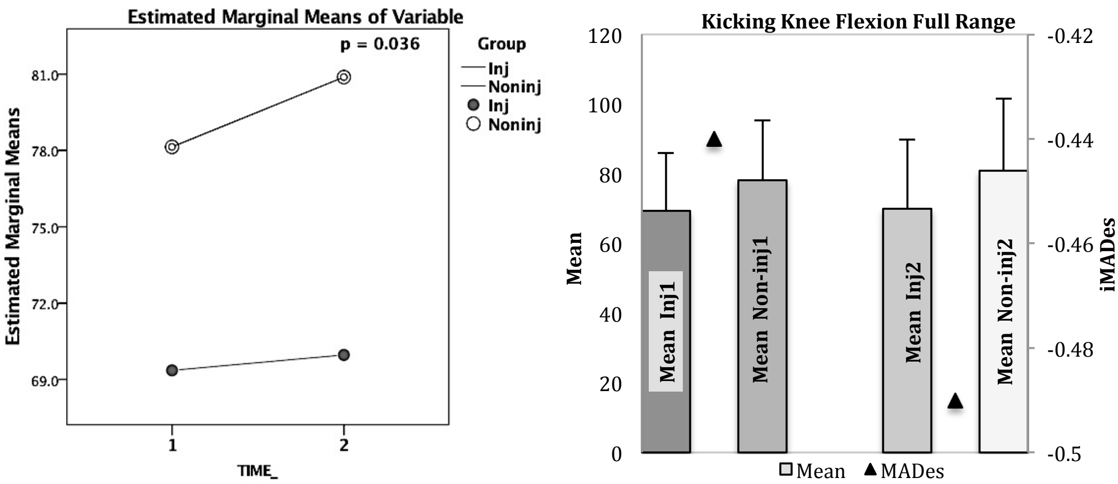

Figure 10: **Kicking knee flexion full ROM (ANOVA)**. Mixed ANOVA results significant group main effect. Group mean, MAD and between group within assessment iMADes.

A significant interaction of group and time was identified for lumbar flexion maximum ROM, $F\ (1, 27) = 4.46$, $p = 0.044$ (Figure 11). Utilisng a simple test of effects to assess pairwise relationships a statistically significant difference was identified for lumbar flexion in the non-injured group ($p = 0.021$). The non-injured group demonstrated greater maximum ROM in the first assessment and a significant reduction in maximum ROM over time.

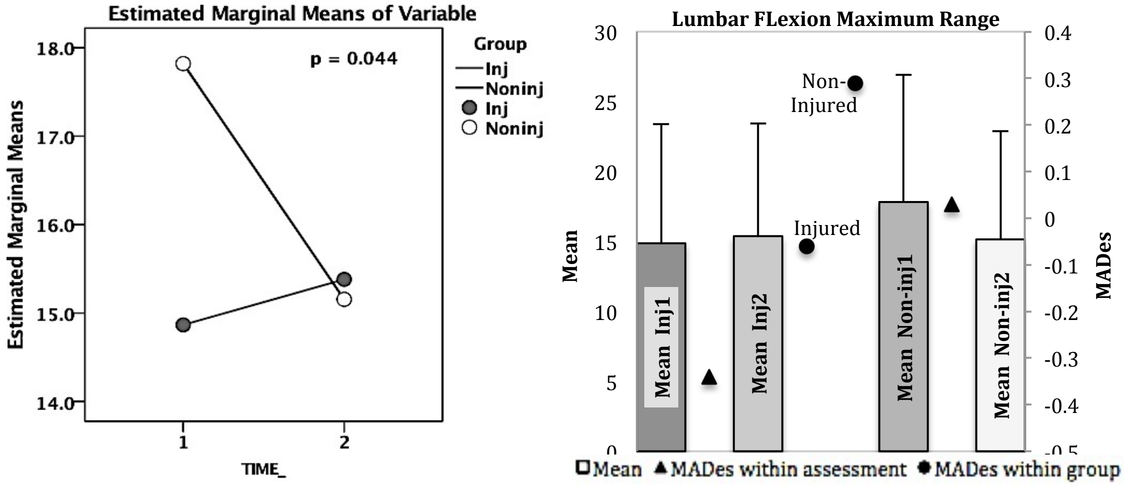

Figure 11: **Lumbar flexion maximum ROM (ANOVA)**. Mixed ANOVA results significant interaction of group and time. Group mean, MAD, between group within assessment and within group between assessment MADes.

A significant main effect was identified for lumbar rotation full ROM, with players demonstrating reduced movement in the second assessment, F (1, 27) = 6.61, p = 0.016, = 15.77, p = 0.001 (Figure 12).

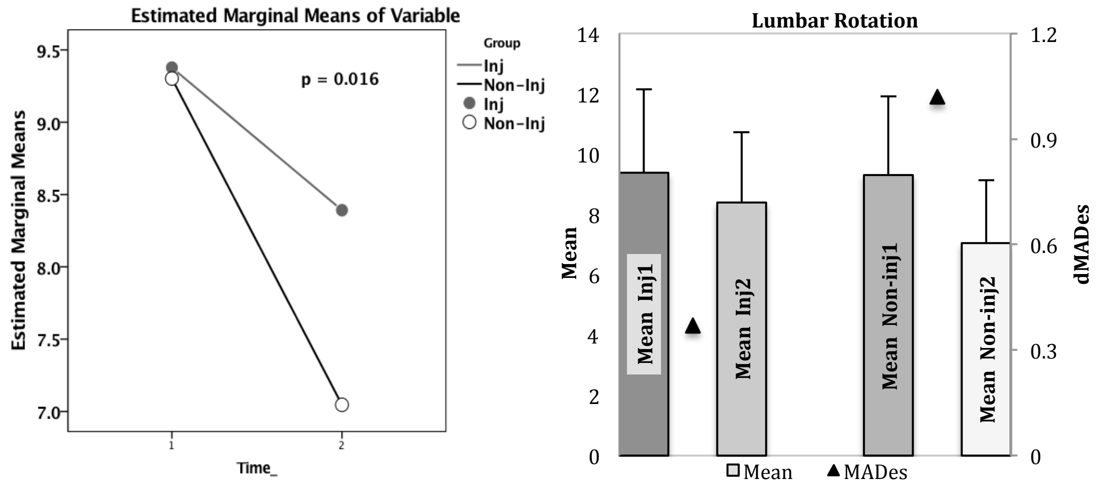

Figure 12: **Lumbar rotation full ROM (ANOVA)**. Mixed ANOVA results significant main effect of time. Group mean MAD and within group between assessment dMADes.

A significant main effect was identified for lumbar lateral flexion, with the injured group demonstrating greater movement for both maximum ROM, F (1, 27) = 6.73, p = 0.015 and full ROM, F (1, 27) = 10.25, p = 0.003 (Figure 13).

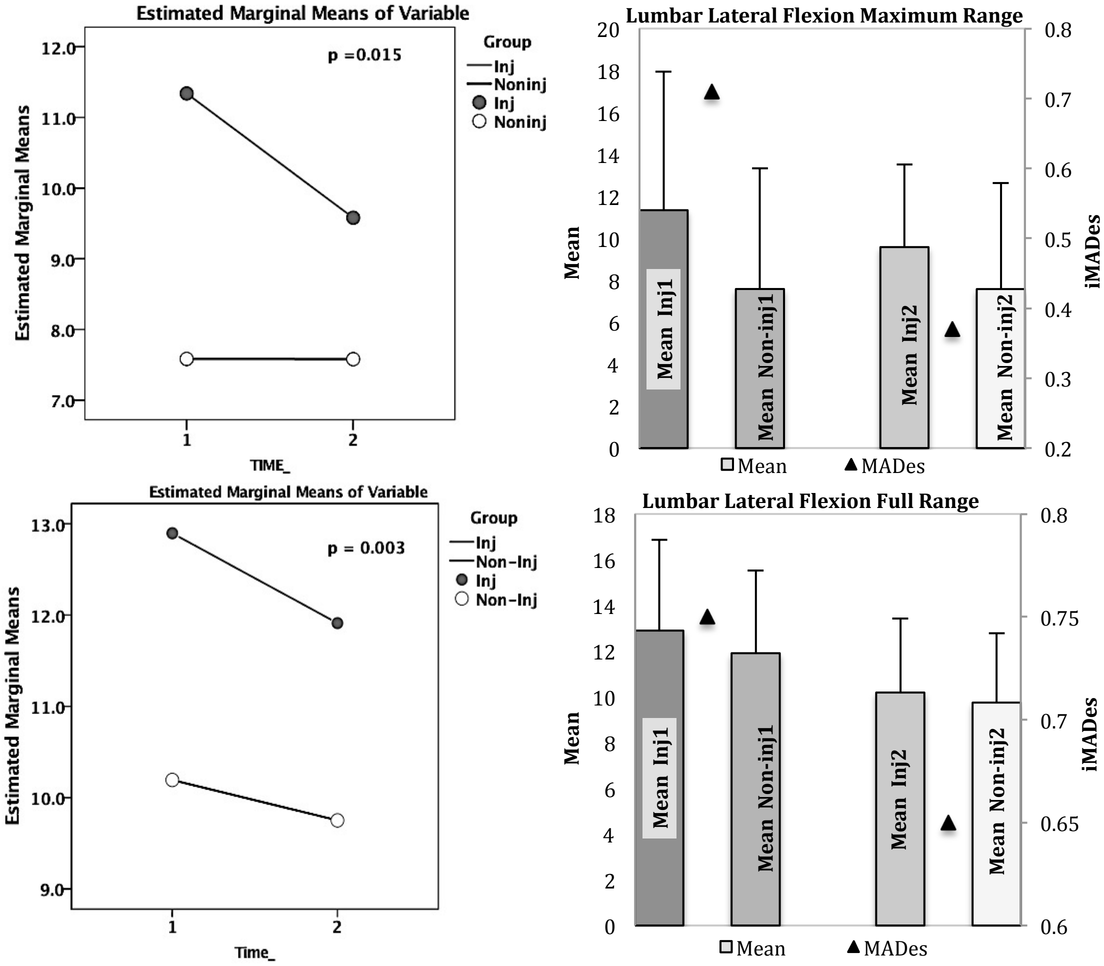

Figure 13: **Lumbar lateral flexion maximum and full ROM (ANOVA).** Mixed ANOVA results significant group main effect. Group mean MAD and between group within assessment iMADe

A significant main effect was identified, with players demonstrating reduced movement in the second assessment for both thoracic flexion maximum ROM, (F (1,27) = 6.99, p = 0.013) and full ROM, F (1,27), 6.38, p = 0.018 (Figure 14).

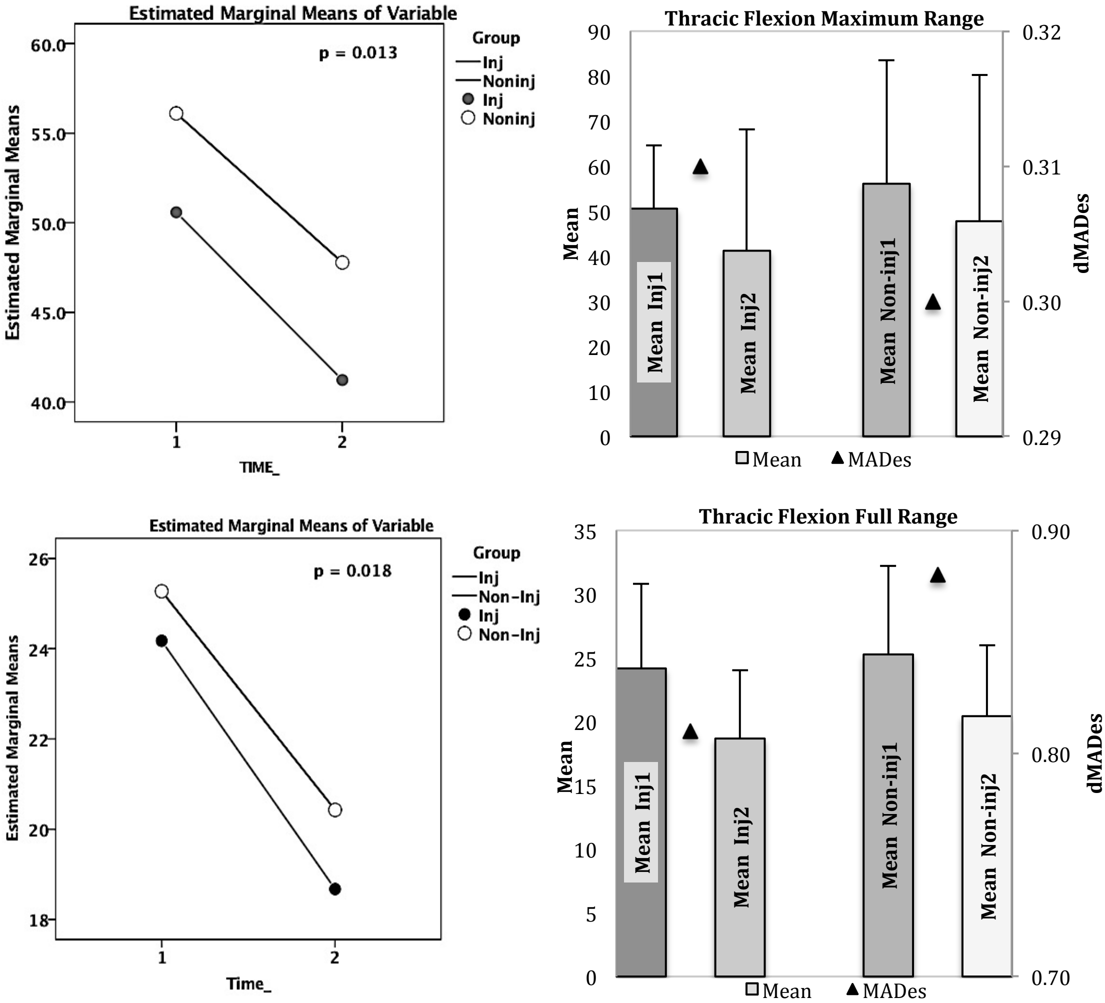

Figure 14: **Thoracic flexion maximum and full ROM (ANOVA)**. Mixed ANOVA results significant main effect of time. Group mean, MAD, within group between assessment dMADes.

A significant main effect was identified for thoracic rotation full ROM, with the injured group demonstrating greater movement, $F\ (1, 27) = 4.67$, $p = 0.040$ (Figure 15).

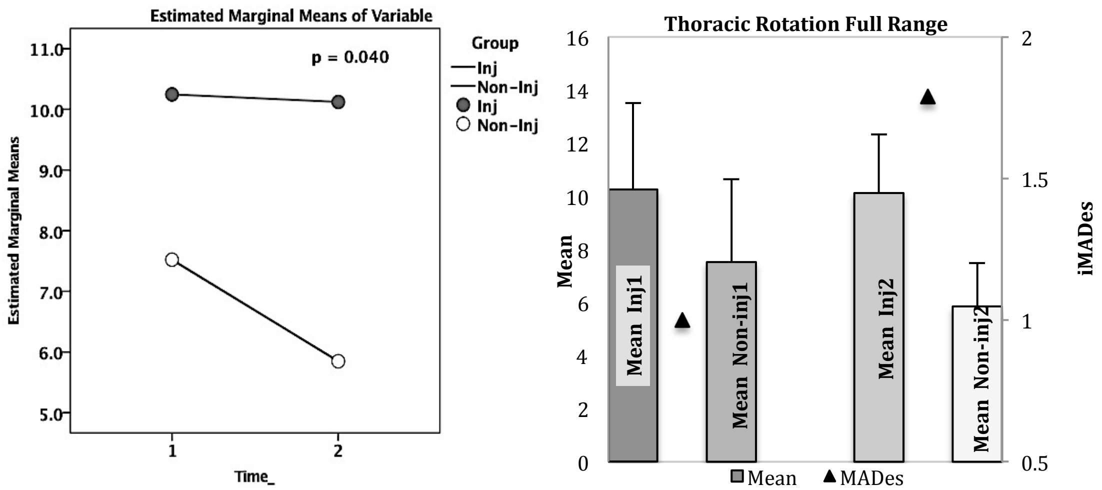

Figure 15: **Thoracic rotation full ROM (ANOVA)**. Mixed ANOVA results significant main effect of group. Group mean MAD and between group within assessment iMADes.

A significant main effect was identified, for thoracic lateral flexion maximum ROM, with players demonstrating reduced movement in the second assessment, (F (1,27) = 5.07, p = 0.033 (Figure 16).

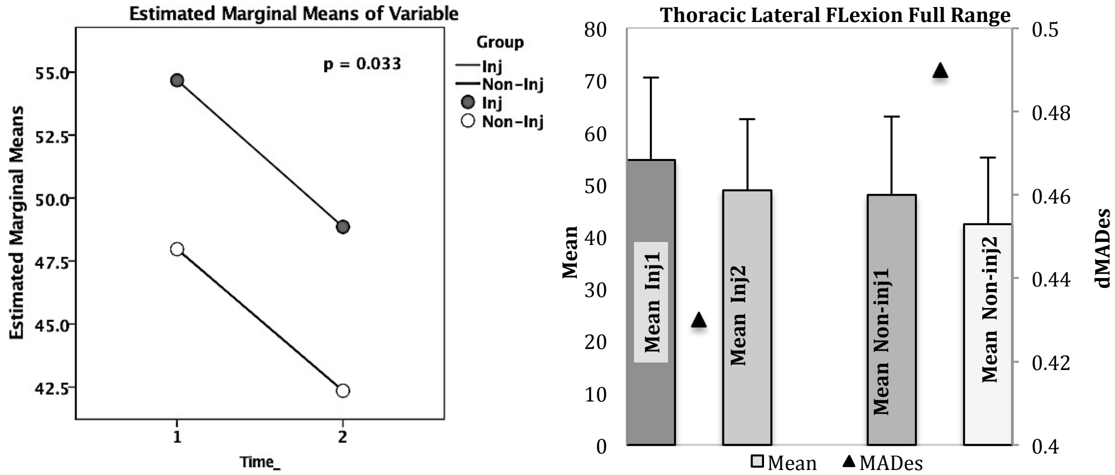

Figure 16: **Thoracic lateral flexion maximum ROM (ANOVA)**. Mixed ANOVA results significant main effect of time. Group mean, MAD and within group between assessment dMADes.

Coordination Variability Analysis

Significant main effects of group F (1,27) = 6.50, p = 0.017 and of time F (1,27) = 6.70, p = 0.013 were identified for the coupled angle variability of support leg knee flexion-pelvic side bend (Figure 17). The injured group demonstrated greater coupled variability during both assessments and a significant reduction in coupled variability in the second assessment.

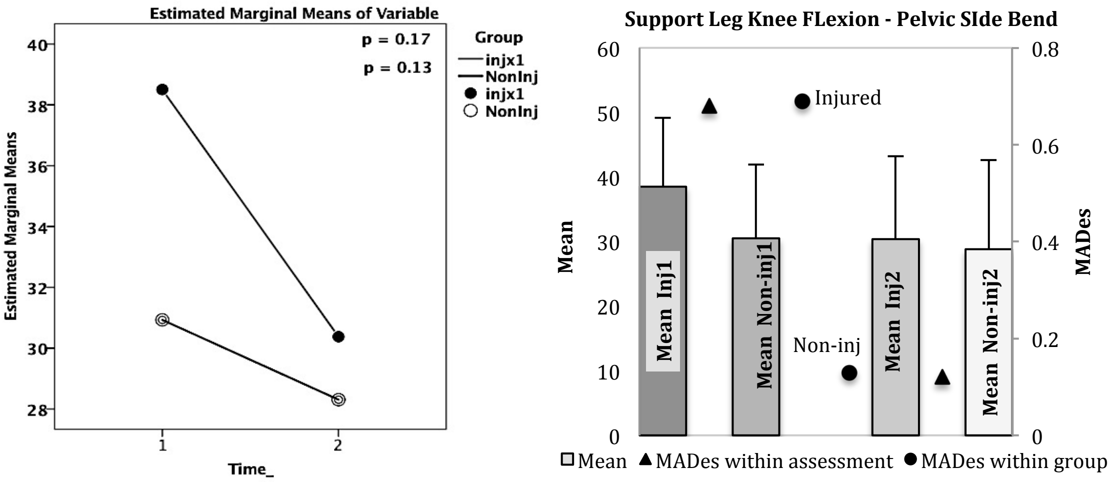

Figure 17: **Support leg knee flexion-pelvic side bend coupled angle variability (ANOVA).** Mixed ANOVA results significant main effect of group and time. Group mean, MAD, between group within assessment and within group between assessment MADes.

Mixed ANOVA analysis was undertaken on all of the kinematic variables assessed (single joint, COM and coupled angles); however, no further statistically significant main effects or interactions were identified.

Spatiotemporal Analysis

SPM analysis of the kinematic data (single joint, COM & coupled angle) also highlighted a number of significant between-assessment findings in the non-injured group (Appendix G).

Movement was not significantly different for the majority of time during the task for the single joint variables of kicking hip flexion, pelvic side-bend and lumbar flexion. However, the critical threshold was exceeded in the non-injured group at 44-46%, 8-25% and 40-75% respectively indicating significant within group between assessments differences at these points. The precise probability that a supra-threshold cluster of this size would be observed in repeated random samplings was $p = 0.049$ for kicking hip flexion, $p = 0.012$ for pelvic side bend and $p = 0.025$ for lumbar flexion.

SPM analysis of pelvic rotation-thoracic rotation coupled angle variability in the non-injured group was not significantly different for the majority of the kicking task. However, the critical threshold was exceeded at 3-7%. The precise probability that a supra-threshold cluster of this size would be observed in repeated random samplings was $p = 0.031$, indicating a significant within group between assessment difference in coupled angle coordination variability for this variable in the non-injured group.

SPM analysis was undertaken for all of the kinematic variables (single joint, COM & coupled angle variability) and no further statistically significant findings were identified. However, four non-significant but notable observations were made from the vector coding coupled angle data during between group comparisons in the first assessment. Differences in coordinated joint variability were observed between groups for kicking knee flexion-thoracic rotation at 15% and 53%, kicking hip flexion-lumbar rotation at 3% and kicking hip flexion-pelvic rotation at 3%. In addition, non-statistically significant but notable between assessment differences for kicking hip flexion-thoracic lateral flexion coupled angle coordination variability were identified in both the injured (83%) and non-injured (70%) groups.

Effect of Injury to Assessment Timing

A simple linear regression was undertaken, which identified a significant relationship between changes in lumbar rotation full ROM and the number of days between injury incidence and the second assessment. Lumbar rotation full ROM reduced significantly over this time period. Preliminary analyses were performed to confirm that no violation of assumptions for normality and linearity occurred. A significant regression equation was found, F (1, 14) = 9.01, p = 0.010), with an R^2 of 0.410. Predicted lumbar rotation for participants is equal to 0.627° + 0.024 (days from injury) when time from injury to second assessment is measured in days. Lumbar rotation full ROM was effected by 0.024° for each day between injury and the second assessment. The following variables were subject to similar post hoc testing when a significant effect over time was identified or if a notable between assessment change was identified following examination of effect size: maximum kicking hip velocity, maximum kicking foot velocity, maximum and full ROM lumbar lateral flexion, maximum and full ROM thoracic flexion, hip flexion-lumbar rotation and support leg knee flexion-pelvic side bend coupled angle variability. However, no further significant regression equations were identified.

Group Descriptive Analysis

The results tables from the descriptive analysis (Appendix H) present the group mean scores, the $dMAD_{es}$ for within group change over time, and the $iMAD_{es}$ for between group changes during each assessment. In relation to single joint & COM variables, the non-injured group demonstrated an average trend for higher mean movement scores in the first assessment but a notable decrease in mean movement overall during the second assessment when compared to the injured group.

The MAD scores were also calculated, which provide an indication of movement variability during each assessment for the injured and non-injured groups. Descriptive analysis demonstrates that variability was on average greater in the injured group during both assessments for the majority of the variables assessed (single joint & COM).

Intra-individual Descriptive Analysis

Results for injured participant 3 are presented (Figure 18) as an exemplar graph of how FMP results may be displayed for individual mean, MAD and $dMAD_{es}$ data. The results for all participants (n = 29) (Appendix I) represent the intra-individual descriptive analysis for the 29 variables assessed. These results present the mean scores from both assessments and the intra-individual effect size difference in the mean over time between assessments ($dMAD_{es}$). In addition, the individual MAD for each variable is presented as a representation of movement variability during each assessment. Overall the individual results demonstrate the broad variations in movement strategy employed by different individuals to complete the kicking task and also the diverse levels of within-assessment-variability that were present.

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Variable	RightHippFlexion	HipAbduction	KneeFlexion	SupKneeFlexion	PelvicSideBend	PelRotation	LumbarFlexion	LumbarRotation	LumbarLateralFlexion	ThorFlexion	ThorRotation	ThorLatFlexion	LumbarAngularVelocity	ThoracicAngularVelocity	PelvicRotationalVelocity	KickHipVelocity	FootVelocity	COMDisp	ComX	HipFlex-LspRoation	PelSideBend-LspRot	SupKneeFlex-PelSideBend	HipFlex-PelRot	KneeFlex-ThorRot	HipFlex-ThorLatFlex	HipFlex-ThorRot	PelRot-ThorRot	HipFlex-LspFlex	PelSideBend-ThorRot
Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

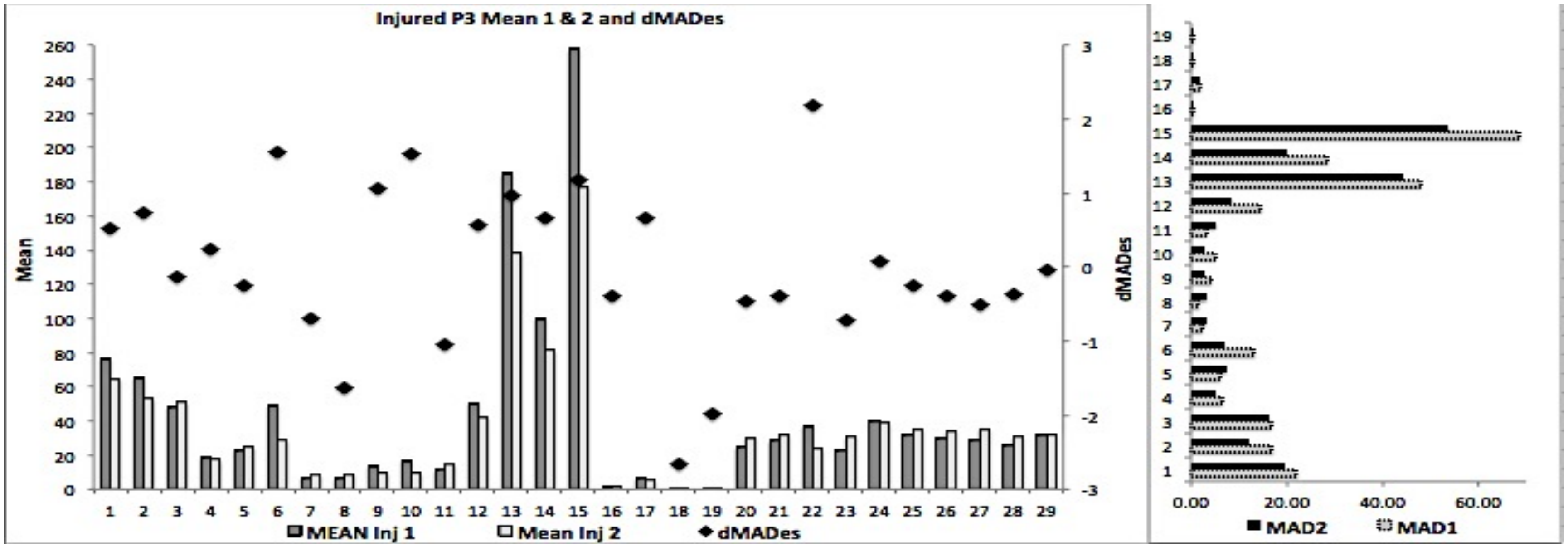

Figure 18: Example Functional Movement Profile. Participant 3 mean for assessments 1 & 2, between assessments dMAD$_{es}$ for all kinematic variables assessed (single joint, COM & coupled angle, n = 29) and MAD for single joint & COM variables (n = 19). For individual assessments the full ROM scores were utilised. *Negative effect sizes indicate larger mean scores in the second assessment. Horizontal axis = mean and dMAD$_{es}$ scores (1-29). Vertical axis = MAD scores (1-19)

Chapter 6 Discussion

6.1
Summary of Findings

The aim of this research project was to decipher if the kinematic movement strategies employed during the sub-maximal inside-of-the-foot pass kick could aid in injury prediction or provide information about how movement may change and adapt over time or as a response to injury. This was achieved in a number of ways. In the pilot and principal studies evidence was provided to support the application, efficacy and repeatability of a markerless motion capture system for measuring kinematic parameters during certain functional tasks. Further, from the data provided in the principal study it has been possible to identify and present an original global picture of the movement strategies employed during the sub-maximal inside-of-the-foot pass kick including adaptations that occur over time and differences that exist between injured and non-injured participants. This also includes the spatiotemporal relationships of the various regions throughout the kinematic chain during this sport specific task. During the first assessment, between groups kinematic differences were identified that may support the possibility of applying specific kinematic markers to aid injury prediction. Significant differences in mean group movement variability were identified and notable differences in variability were apparent between groups during both assessments. There was significant variation in the movement strategies employed to complete the task both over time and between individuals and groups. Overall the data would suggest that, although not totally disparate, the injured and non-injured groups did employ different kinematic strategies to complete the kicking task and that these differences may be correlated with injury causation and adaptation of movement strategy following recovery from injury. Also apparent from the present data was that group comparison methods for assessing functional movement might hold certain disadvantages when compared to intra-individual analysis. To that end, application of an individualised measurement and comparison tool, such as the Functional Movement Profile (FMP) demonstrated in this study, may be the logical way to proceed in order to improve our understanding of injury causation and adaptation mechanisms.

6.2
Application of Markerless Motion Capture

As previously discussed, a number of clinical assessment methods have been developed to assess and measure individual functional movement (Cook, 2014a) and in some instances act as injury prediction tools (Kiesel, 2007). Whilst being excellent clinical tools and holding many benefits, such as ease and low cost of application, they only seek to measure gross trunk movements and are not designed for or perhaps capable of identifying the subtle kinematic changes that were obvious in the present data. Therefore, in regard to measurement capacity there may be real benefit to applying more precise motion analysis tools in order to identify small and detailed kinematic changes during task specific movements. Unfortunately, a major obstacle to the clinical application of more precise methods is that real world access to the type of markerless motion capture system employed in this study is limited. Only a small number of these types of system are in operation at present, a fact due most likely to the expense of such a system with the approximate cost being £60,000 GBP. However, it is valid to note that once established, this particular markerless system is extremely user friendly. It can be operated with minimal training (less than thirty minutes of instruction), only limited anatomical knowledge is required to operate the system and even complex functional tasks can be assessed very quickly, often taking less than 5 minutes. Even considering the financial restraints of such complex measurement systems, it may still be important to develop methods of incorporating the findings from more sensitive instruments into readily available clinical tools and it is apparent from the literature that there is a growing interest in doing just that. A number of authors have investigated the potential use of the Kinect (Microsoft), a relatively cheap and readily available camera based sensing system for application as a markerless motion analysis instrument for biomechanical analysis (Clark, 2013, Gray, 2017, Pfister, 2014, Schmitz, 2015). For example, the Kinect has been successfully employed to measure gait parameters during walking (Xu, 2015) and as a potential screening tool for increased ACL injury risk (Gray, 2014). Mauntel et al (2017) employed a Kinect camera to analyse the movement quality of participants completing Landing Error Scoring System (LESS) assessments and compared the results to traditional visual rater techniques made from video recordings of the tests, the aim of which was is to assess the accuracy and time efficacy of a markerless motion captures system to replace the visual rater approach, which they propose may be overly time consuming to be practical for the clinical environment. The study identified that the single camera markerless system demonstrated sufficient accuracy to match expert raters and similar to the present investigation, that it also showed notable advantages in regard to ease of application and time saving (Mauntel, 2017). This study highlights the potential benefit of incorporating more sensitive motion capture technology into the functional assessment environment (Mauntel, 2017). However, it is the belief of this author that the potential of markerless based analysis may be far greater in regard to improving our understanding and capacity to measure human motion during functional tasks. One possible future approach may be to investigate potential predicative and adaptive kinematic injury traits during a number of functional tasks utilising markerless motion capture & analysis and then to adapt the present clinical tools and assessment procedures (Cook, 2014a, McKeown, 2014) to reflect the new information or insights that are gained.

As highlighted when reviewing the literature, there is contention regarding the efficacy of markerless motion analysis methods for human motion capture in the field of biomechanics. The principal study involved a longitudinal approach for data comparisons, therefore it was necessary to identify if the system could repeatedly capture kinematic information within and between data capture sessions. This was achieved by the inclusion of a small pilot study examining four participants undertaking multiple repetitions of a functional task during two separate recording sessions. Although the principal study involved assessment of the sub-maximal inside-of-the-foot pass kick, an alternative task, the STS/STS was utilised in the pilot study and was deemed suitable for the following reasons: although the movement requirements of STS/STS differ from those of the sub-maximal inside-of-the-foot pass kick there are similarities between the two tasks. Both require displacement of the COM and involve multi-region coordinated movement throughout the kinematic chain from the ankle to the spine, albeit in the sagittal plane for the STS/STS. In addition, the STS/STS task is a common daily functional movement completed by most individuals (Schenkman, 1990). Importantly, the ability to utilise a prop during the STS/STS task, in this case a chair to standardise the depth of the sitting movement, reduced variability in respects to the end point of movement and thus facilitated improved estimation of the systems capacity for repeated measurements.

With regard to the utilisation of the markerless motion capture system as a reliable instrument to capture and analyse repeated human kinematic movements, the pilot study undertaken, as part of this research project would suggest that this technology is fit for purpose. The pilot study demonstrated that the markerless motion analysis system employed provided excellent levels of repeatability during trials of a functional task. The data collection process undertaken during this research also highlighted two further important benefits of applying a markerless data capture approach particularly for team assessment or multi region and repeated measures analysis. Due to the auto synchronisation of the present system and the method the system employs for acquiring and measuring kinematic markers, (Poppe, 2007) data capture sessions were extremely time efficient and user friendly. Calibration of the system to each new participant took approximately one minute and the full recording of the required kicking repetitions was completed in less than ten minutes for each participant. In addition, the present system did not require extensive training or specific anatomical knowledge to be operated when carrying out the data capture sessions. These benefits are especially pertinent when compared to the ‘gold standard’ marker-based alternatives (Gorton, 2009, Mundermann, 2006a, Szczerbik, 2011).

6.3
Kinematics During the Sub-Maximal Inside-of-the-Foot Pass Kick

As previously stated this research investigated the kinematic movements of a large number of discrete variables (single joint, COM & coupled angles) during repeated trials of sub-maximal target directed inside-of-the-foot pass kicks. To date no previous literature has been identified that has investigated such a broad number of kinematic variables or provided such a comprehensive window into the kinematic requirements of undertaking this sports specific task. Therefore in the first instance these results provide an original general overview of the mean kinematic movements employed for the discrete variables assessed. In addition to measuring the ROM attained, it is also important to understand when during the task specific movement occurs (Caballero, 2014, Stergiou, 2011, Yoshioka, 2009). This provides a clearer insight into the spatiotemporal aspects of kicking, contributes to the general knowledge base of how this functional task is completed and provides an insight into potential differences in movement strategy that are employed throughout the kinematic chain between groups and individuals. To that end, a selection of data for variables in the spine, pelvis and lower extremity are presented for the full duration of the kicking movement in the injured and non-injured groups. These variables were selected as they provide a suitable representation of the various regions of the kinematic chain during the kicking task (Nunome, 2002, Shan, 2005). When observing the combined mean kinematic results (single joint, COM) from both assessments and comparing the movement patterns of the injured and non-injured groups, there is an obvious difference in the kinematic properties that the two groups present. Although not necessarily statistically significant, for all of the single joint variables displayed other than for lumbar lateral flexion, the non-injured group exhibited greater full ROM than their injured counterparts throughout the kinematic chain. In regards to the velocity of joint movement the reverse is true with the injured participants using greater mean rotational and linear velocity throughout the kinematic chain during the kick. It is not possible, utilising the data from the present study, to provide a suitable explanation as to why these joint ROM and joint velocity kinematic variations occurred between groups as muscle force, power and torque generation were not measured. Therefore, future investigation as to the potential mechanisms underlying these findings is recommended.

Previous literature describes the ability of football players to adapt their pelvic and lower extremity kinematics during different types of kick. This suggests that the players were able to modify their movement strategy for optimum completion of the required goal orientated task (Levanon, 1998, Nunome, 2002). The present study involved assessment of a goal-orientated task with participants required to repeatedly hit a target three metres away. As one might expect with elite level football players the target accuracy rate was very high and limited excess kicks were required to complete each assessment ($\bar{x}$ = 10.4). Although no measurement of ball contact accuracy was made, the ability to consistently hit the target would indicate a high level of repeatability in respect to end-point foot to ball contact. This repeatability of end-point contact was attained even though the players employed broad variations of kinematic movements throughout the kinematic chain during the task. These results are in keeping with the findings from the literature demonstrating repeatable end-point accuracy during sports specific tasks with accuracy attained independent of the degrees of freedom employed in related joint regions. (Chow, 2006, Robins, 2006, Scholz, 2000, Yang, 2005).

Shan & Westerhoff (2005) identified formation of a 'tension arc' during the maximal power instep kick that is more apparent in experienced players. They suggest this enables increased power creation and transmission throughout the kinematic chain and that it is a sign of increased kicking proficiency. The present study also identified formation and release of a tension arc type mechanism but perhaps of more interest is that this mechanism differed from that described previously (Shan, 2005). In fact in some respects the opposite movement occurred, specifically in the spinal region.

Some of the difference in findings may be explained by the method in which variables were assessed, for example the present study examined the thoracic and lumbar spine as separate functional entities rather than the global measurement of trunk movement that had previously been employed (Shan, 2005). However, it is also likely that as with adaptations that take place in the pelvis and lower extremity during kicking (Levanon, 1998, Nunome, 2002), there is also modification of spinal kinematics to meet the requirement of the specific kicking task, depending on the type of kick employed. This would explain how a tension arc mechanism could be present in both types of kick whilst differing dramatically in its kinematic properties. The ability to utilise different forms of tension arc mechanism during different types of kick whilst maintaining high levels of end point accuracy is further evidence of the abundant movement variations that are employed by an individual to complete diverse goal orientated tasks.

6.4
Variability

A number of authors have articulated the opinion that rather than being unwanted noise, movement variability is a necessary if not vital aspect of human kinematic movement (Davids, 2003, Hamill, 2012, Stergiou, 2011). Davids, Lees & Burwitz (2003) describe the functional role of movement variability, and Seifert, Button & Davids (2013) discuss the importance of movement adaptability for expert performance. Many authors are of the opinion that variability in movement contributes to maintenance of a healthy functional dynamic system and represents the ability of a healthy functioning organism to adapt to perturbations and thus reduce the risk of injury (Claeys, 2011, Hamill, 2012, Moseley, 2006, Stergiou, 2011). More recent research has proposed that neural and motor variability are interrelated, with larger variation in neural preparation correlating with increased kinematic variability (Lisberger, 2015). These centralised neural origins serve as further confirmation of variability being an inherent part of the human movement strategy. The fact that variability of movement is in part a centrally mediated neural process also supports the argument for assessment of movement at an individual level and that a 'perfect pattern' for task completion does not exist when analysing and comparing inter-individual movements (Latash, 2012a, Latash, 2012b). Factors such as repetition, practice, learning and reward may refine the temporal elements of movement variability to achieve specific tasks (Pekny, 2015, Wilson, 2008, Wu, 2014). However, each time we complete a task the movement and variability of movement that we employ is a unique process that portrays distinctive individual motor characteristics (Haar, 2017). This is supported by the findings from the present data with both inter-individual and intra-individual variability identified. No two participants completed the task by employing the exact same movement strategy and each individual employed movement variations in all of the regions assessed during each repetition of the task. Considering these findings, perhaps as has been suggested, when examining human movement the focus should be more exploration of optimal variability patterns during task completion rather than trying to emulate the perfect movement strategy (Latash, 2012b).

Although the potential role that variability can play in aiding identification of pathology is becoming more widely accepted, whether increased variability is the sign of a healthy or unhealthy system is still a contentious issue. Contrary to evidence from the field of musculoskeletal injury (Hamill, 2012), investigation of variability and its correlation to neuropathology, specifically during standing and walking has identified that in the majority of pathological conditions examined increased variability was present indicating that higher variability is correlated to an unhealthy system (König, 2016). However, many of the investigations previously undertaken in the field of musculoskeletal injury have been focussed on joint coordination variability. Considering the important contribution that the nervous system makes to the generation of movement variation (Haar, 2017, Lisberger, 2015) and the differing elements of variability assessed, perhaps it is not surprising that investigations of the effect of neurodegenerative pathologies and musculoskeletal injury would yield differing results (Hamill, 1999, Hamill, 2012, König, 2016, Lord, 2013). Interestingly, in studies of both neurodegenerative pathology and musculoskeletal injury a common thread does emerge; authors in both fields propose a healthy performance 'window' in regards to variability. In the case of neurodegenerative disease this window of movement variability during gait performance may be employed to discriminate between healthy and pathological populations (König, 2016). Stergiou and colleagues (2006, 2011) discuss the importance of variability and suggest that an overly rigid or an unstable system that occurs as a result of too much or too little variability is less likely to cope sufficiently with perturbations. In the field of musculoskeletal medicine, authors propose a correlation between healthy function and levels of variability in regard to coupled joint actions (Hamill, 1999, Hamill, 2005, Hamill, 2012) and suggest that optimum injury free kinematic function exists in an 'optimum window of healthy high coordination variability' (Hamill, 2012) (Figure 19).

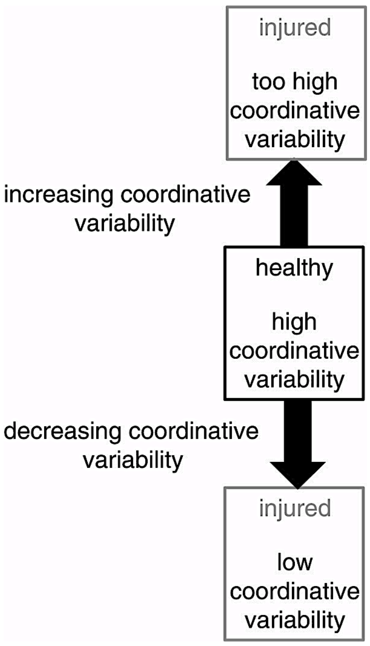

Figure 19: Optimum window of higher healthy coordinative movement variability (Hamill, 2012).

If we hold to the theory of increased coordinated joint variability being indicative of a healthier functioning system (Hamill, 2012) then we might expect to find greater levels of this form of variability in the non-injured group during the present study; however, this was not the case. Of the 10 coupled joint variables assessed only one, support knee flexion-pelvic side bend, was significantly different between groups, with the injured participants exhibiting greater mean coordinated joint variability. In addition, descriptive analysis of the effect size for the coupled angle variables revealed that group mean coordination joint variability was larger in the injured group for more variables particularly in the first assessment. It is however important to note that these findings should be interpreted with caution as the importance of the effect sizes identified is debatable, with only two variables in each group exhibiting an effect size above 0.2 (Cohen, 1988, Glass, 1981).

It has been suggested that coordinated joint variability may increase over time as skill increases (Wilson, 2008) and this was the case to a small degree in the non-injured group with relative increases in coordinated joint variability during the second assessment. However, no increases in coordinated joint variability were observed in the injured group and therefore it is not possible to judge if skill played a part in the changed variability experienced by the non-injured group.

The inferential statistical analysis when considered in conjunction with the descriptive findings indicate that in the present research insufficient evidence is provided to support the proposition that increased coordinated joint variability is correlated with a healthier system.

SPM analysis of the coupled angle variables also identified that the kicking knee flexion-thoracic rotation, kicking hip flexion-lumbar rotation and kicking hip flexion-pelvic rotation couplings all demonstrated non-significant but notable between group differences in mean intra-individual coordinated joint variability throughout the entirety of the kicking action during the first assessment. Further exploration of these particular coupled joint variables may be beneficial in future investigations to decipher if any meaningful insights can be gained.

In respect to descriptive examination of the discrete variable (single joint & COM) results an interesting pattern is exhibited. The injured participants demonstrated larger average group MAD (group variability) scores during both assessments, with the difference between groups being more pronounced in the first assessment. It has been suggested that measurement of variability in a single body segment may not provide sufficient information to evaluate the true extent of the motor variability that is present (Srinivasan, 2012). However, by examining the variability of multiple individual segments throughout the kinematic chain it is likely that a reasonable estimation of global movement variability could be attained. The findings from the present study

suggest that, in general, mean levels of movement variability were different between groups and higher in the injured participants. This may indicate that the injured group were functioning with a less stable system leading to a reduced capacity to deal with perturbations (Stergiou, 2011). What is not clear from the present findings is if or how these differences contributed to the aetiology of injury. This is an area of investigation that requires further attention in future exploration of coordinated joint variability.
If we review the MAD data at an individual level for each participant, the picture is complicated further. There are definite similarities in the way the participants move during the kick; however, levels of variability are different within each individual and between individuals during both assessments. An example of the levels of intra-individual variability during the kick is presented (20). This demonstrates, with the use of a segment trace for the foot COM, the variability present in the kicking foot during three separate kicks.

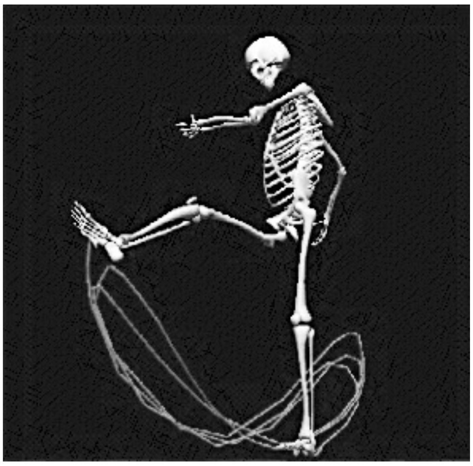

Figure 20: Kick Variability Example. Segment trace of the foot during three separate kicks from one participant. Graphics produced by The MotionMonitor® Acquisition, Visualization & Biomechanical Analysis Software © (Innovative Sports Training, 2011).

The intra-individual variability identified is important as it adds support to two issues previously discussed. Firstly it adds weight to the argument that there is no optimum movement pattern for individuals to aspire to (Davids, 2000). Secondly, it demonstrates that group kinematic data comparisons do not fully represent individual movement and instead variability should be analysed with boundaries set and comparisons made based on individual and not group level analysis results.

6.5
Injury Prediction

We can see from the literature (Augustus, 2017, Kellis, 2004, Lees, 2002, Levanon, 1998, Nunome, 2002, Opavsky, 1988, Orloff, 2008, Parassas, 1990) that imposed adaptations, e.g. power of the kick, support foot positioning, type of kick and approach angle can lead to changes in biomechanical requirements throughout the kinematic chain when kicking. Considering the levels of movement variation present as a result of these imposed adaptations it is likely that different functional tasks would further broaden the variety of movement strategies required for task completion.

The present study also identified large variations in the movement strategy employed within and between groups independent of injury occurrence. This is in keeping with a recent investigation that examined changes in movement during functional screening tests in football players over an extended period of time (Bakken, 2017). Considering these factors, the scale of the problem becomes clear in respect to the difficulty of utilising kinematic findings as markers for injury prediction. In fact considering the complexity highlighted it is not surprising that some authors doubt that screening tests will ever be effective as injury prevention tools (Bahr, 2016).

One of the aims of the present study was to ascertain if markerless motion capture and analysis could be of benefit in identifying kinematic movement traits that may be used to predict increased injury risk. Logistic regression analysis of the baseline data identified that thoracic flexion maximum ROM and support knee flexion-pelvic side-bend coupled angle variability both exhibited movement characteristics that differed between the injured and non-injured groups. These characteristics may indicate injury predictive value for these variables. In addition, mixed ANOVA analysis identified a significant difference between groups, and over time, for support knee flexion-pelvic side bend coupled angle variability with the MAD_{es} demonstrating that the difference was primarily in the first assessment. Therefore, in regard to the sub-maximal inside-of-the-foot pass kick it would seem that athletes who demonstrated certain kinematic parameters i.e. reduced mean thoracic flexion and increased mean support knee flexion-pelvic side bend coordination variability during the first assessment were potentially more at risk of experiencing an injury. Increased thoracic flexion has previously been identified as a risk factor for knee ligament injury on landing but not during kicking

(Blackburn, 2008). The relationship between the support knee and pelvis has previously been described in respect to effects on kicking performance and generation of kicking foot velocity (Inoue, 2014) but not in respect to injury. The present findings are not conclusive evidence of a correlation between the variables identified and causation of injury, however they do demonstrate significant between group differences in the first assessment and that a potential relationship between these variables and injury development did exist during this specific kicking task.

Although the present data indicates potential relationships between injury and some movement variables, is this sufficient for these variables to be employed as injury prediction markers? Bahr (2016) would argue not and suggests three criteria that need to be met before an injury prediction method can be verified as effective; One, a strong relationship must be identified between the marker and injury risk. Two, the test properties need to be examined in relevant populations, using appropriate statistical tools. Three, it must be documented that a screening-based intervention is more beneficial than intervention alone (Bahr, 2016). It could be argued that this third criterion is related less to screening and more to intervention prescription. It could also be argued that the markers identified and the methods employed in this study meet the first and second criteria respectively. However, the underlying fundamental problem with the criteria proposed by Bahr (2016) and with the majority of the present methods that seek to apply biomechanical boundaries to facilitate injury prediction (Bardenett, 2015, Cook, 2014a, Kiesel, 2007, Leetun, 2004, McKeown, 2014, Paterno, 2010, Zazulak, 2007a, Zazulak, 2007b) is that they seek to compare the individual's movement to what is deemed a 'group norm' and not the individual to themselves. As previously highlighted this approach may be inherently flawed as both the literature and the present data demonstrate that individual movement is highly variable and task dependent making establishment of accurate 'normal' group biomechanical boundaries difficult and inter-individual comparisons potentially ineffective. Therefore, although the present findings may have identified potential kinematic markers to aid injury prediction during this particular kicking task the data also supports the argument for individualised analysis and comparison.

Even with the application of intra-individualised kinematic measurement and comparison it is still important to remember that there are a multitude of factors that may contribute to injury/re-injury, including; contact trauma, athlete beliefs, attitudes, knowledge and behaviours, sports equipment and protective clothing, the sport setting or context, climatic conditions and the psychological state of the athlete (Gledhill, 2017, Vriend, 2017). Therefore, whilst kinematic analysis may provide some benefit in the injury prevention theatre, it should be remembered that it's effectiveness may be limited and that it should be employed as one part of an expansive multi-faceted injury prevention strategy.

6.6
Movement Change & Adaptation

As previously highlighted, with the majority of the tests that are currently utilised to measure athlete kinematics from a performance and injury prediction perspective there is a strong reliance on comparing the participant's results to a 'normal' mean cohort score (Bardenett, 2015, Cook, 2014a, Kiesel, 2011, Nadler, 2002). Surprisingly, considering the extensive use of the 'normal' or mean group score for comparison there is a lack of previous investigation identifiable in the literature as to what constitutes normal kinematics especially over an extended period of time. That is, the questions of whether there is an average kinematic 'norm', if this norm alters and the level of alteration between assessments, are still to a large degree unanswered. A number of studies have investigated this question indirectly as part of the examination of other areas of interest, often as part of the assessment of change post surgery or following injury rehabilitation (Goerger, 2015, Hofbauer, 2014, Rohman, 2015). The data in the present study goes some way towards providing answers to these questions. It provides original and extensive information regarding mean group and individual baseline measurements (Stergiou, 2005) and demonstrates the degree of change that occurs over time in player kinematics during the sub-maximal inside-of-the-foot pass kick.

When investigating the role that injury, as an independent variable, plays in kinematic movement adaptation that persists following full recovery, the aim is to accurately describe the relationship between the initial value and the real unbiased change that occurs purely as a consequence of the independent variable. However, identifying if injury is the cause of changes in kinematic starategy is a problematic process. Therefore, when comparing baseline values to subsequent time related change the challenge is to clearly identify changes that were caused as an adaptation to injury and to separate those changes from the normal variability that exists or alters over time within and between participants (Chiolero, 2013) and also the levels of error that occur as part of the measurement and analysis process. Statistical analysis from the present study identified a number of kinematic variables that altered significantly over time within both groups. Lumbar flexion exhibited a significant interaction of time and group, and post hoc analysis identified that a significant change over time (between assessments) occurred in the non-injured group. Perhaps of most interest however, in respect to adaptation that occurred as a result of injury, was the change in support knee flexion-pelvic side-bend coupled angle variability. Significant change over time between assessments was exhibited with mean coordinated joint variability in the injured group reducing significantly in the second assessment. Interestingly this same variable demonstrated significant injury predictive value following logistic regression analysis of the first assessment data. This was the first time this coupled angle variable has been associated with injury; therefore to decipher why this may have occurred it was necessary to examine the contribution that both the support knee and pelvis make to the kick. The support knee has been shown to contribute to kicking performance (Inoue, 2014, Inoue, 2000) and the support leg as a contributor to balance during the kick (Chew-Bullock, 2012). In addition, pelvic stability which has previously been defined as reduced pelvic side-bend during the kick (Lees, 2010) has been proposed as a contributing factor to improved performance during kicking in football. It is obvious that both support knee flexion and pelvic side-bend when viewed as separate regions make an important contribution to the global kinematic strategy during kicking. Is it possible that the fluctuations in mean variability identified for the support knee flexion-pelvic side-bend variable in the injured group, indicate a system that was unstable (Stergiou, 2011) and that lacked the flexibility to respond to injury? Unfortunately this question cannot be conclusively answered from the findings of the present study. However the findings do serve to highlight an area of interest that would benefit from future investigation.

Descriptive analysis of the MAD_{es} scores for the discrete (single joint & COM) variables also provides interesting information regarding changes in movement over time and between groups. The results suggest greater adaptation in movement strategy over time (between assessments) for the non-injured group. This is supported by the findings from the SPM analysis that demonstrated significant differences in phasic movement strategy between assessments for a number of single joint variables and one coupled joint variable in the non-injured group. It is possible that the more pronounced movement changes in the non-injured group indicate a superior capacity to adapt to a more efficient and stable movement strategy (Stergiou, 2011). If this were the case then logic would suggest that the opposite were true for the injured group who therefore demonstrated a relative incapacity to adapt and thus a less flexible system as a result of injury.

Taken as a whole, the present data presents a picture of contrasting changes in levels of movement between groups over time, with the two groups exhibiting notably different movement strategies. Specifically the data suggests that injury was associated with increased mean movement in more variables throughout the kinematic chain and reduced adaptation of the movement strategy over time for the kicking task.

Previous effect size changes have been demonstrated for different technique interventions (Augustus, 2017) and when comparing skill level and coordination (Egan, 2007). However, the present study provides the first example of employing effect size to demonstrate a relationship between previous injury and changes in movement strategy during kicking in football. Nonetheless, the true nature of the relationship between injury and the changes in movement that were identified between groups requires further investigation.

Interestingly for the lumbar rotation full ROM variable, simple linear regression identified a significant change in this variable when the relationship between the timing of injury and the second assessment was analysed. There is no discernable reason why the timing of assessment would have affected only one of the variables. However, this result does suggest that it may be valid in future research to undertake repeated measures at different time points post injury to further investigate the relationship between the time of injury occurrence and assessment.

In respect to movement variability, it has been suggested that the levels present during kicking are relatively consistent and therefore may not fluctuate during assessments on different days (Lees, 2013). In the present study the group MAD scores describe the group mean levels of movement variability that occur within each assessment. If, as suggested (Lees, 2013), levels of variability were relatively unchanging on different assessment days then we would expect to see only small changes or even equivocal group MAD scores when comparing the data from both assessments. This was not the case, as the present data describes notable group difference in the MAD scores independent of injury. This suggests within assessment fluctuations in movement variability on different days and would indicate adaptation in levels of group movement variability as part of the normal inherent motor strategy to complete a task. However, although variability fluctuated on different days, there was a trend in the discrete variables (single joint & COM) for decreased group mean movement variability during the second assessment for both groups. This is in keeping with previous literature that has discussed reductions in elements of variability over time as part of the natural learning process (Müller, 2009). The injured group demonstrated greater variability compared to the non-injured group during both assessments. Conversely the non-injured group exhibited larger variation in the levels of mean variability present during different assessments. Previously it has been suggested that an ideal window of variability may exist during functional tasks and that excessive variability may be indicative of an unhealthy functional system (König, 2016). It has also been postulated that variability in movement allows a level of flexibility in the system to respond to varying environmental and task related needs (Davids, 2003), and that adaptation of movement patterns and the variability therein should be viewed as normal (Latash, 1996). Therefore, is it possible that the larger levels of within assessment variability identified in the injured group are indicative of excessive variability related to unhealthy function? Is it also possible that the relative reduction in variability during different trials represents a system that lacks flexibility to adapt over time to the needs placed upon it? Unfortunately, there is insufficient evidence in the present study to categorically support this proposition but it is clear from the data that levels of group mean variability were inconsistent between groups and that the injured group exhibited a reduced capacity in regard to adaptation of the movement strategy over time.

6.7
Functional Movement Profiling

It is important when undertaking statistical analysis to apply a method that enables investigation of the data in a manner that is appropriate. The present study had two primary requirements for data analysis and representation. Firstly, there was the need to identify possible kinematic predictors for injury and normal kinematic changes over time or as result of injury. For this to be achieved group comparisons of the data were required and quantitative statistical techniques were appropriate. This involved application of a mixture of linear methods, such as mixed ANOVA analysis, and non-linear methods such as SPM. However, when it comes to analysis of individual kinematic adaptation, group comparisons may not be appropriate. Previously it has been proposed that differing individual movement strategies may skew data results when only inter-group comparisons are employed, leading to description of an 'unrealistic average performer' that is not truly representative of any of the actual participants (Dufek, 1995). Therefore it could be argued that the best possible way to examine individual movement alterations and to explore if these alterations are correlated with injury is to compare intra-individual movement and levels of variability whilst completing specific tasks. This is supported by the findings in the present study. If we review the statistical test results and group MAD they describe increased overall variability between assessments for the injured group. However, if we examine intra-individual MAD results a different picture can be seen; for example some of the participants in the non-injured group (participants 13,15 & 29) exhibit greater variability than the majority of the injured perticipants.

A number of authors have discussed the difficulty of comparing inter-individual data or scores for injury prediction (Bahr, 2016, Krosshaug, 2016, Mok, 2016, Smith, 2012) and that there may be no optimum movement pattern for completion of specific sports or functional tasks (Brisson, 1996). In addition, it has been proposed that motion analysis procedures need the capacity to accurately analyse and compare unique individual task specific movement (Ball, 2003, Bartlett, 2005), and that profiling of movement should be focused on individual mechanisms and behaviour for completion of specific tasks. Movement is unique to the individual and also the task (Chow, 2006) and as such must be compared only in the context of individual participant change and not to group averages or 'norms'. By defining normal baselines or boundaries of movement for the individual (Scholes, 2012) it may be possible to identify when and why kinematics change and the further reaching effects this may have. If we consider the levels of variability that have been previously identified in the literature (Bauer, 1997, Dufek, 1995, Egan, 2007, Hamill, 1999, König, 2016, Lees, 2013, Scholes, 2012) and the individual results presented in this study (Appendix I), the argument for individualised mapping of human kinematic characteristics becomes difficult to reject. As previously highlighted, group analysis of the data in this study has demonstrated that large levels of group mean-intra-individual-variability were present, this is very apparent in both the lumbar angular velocity and pelvic rotational velocity variables. However, upon closer examination of the individual data (Appendix I) it becomes apparent that certain participants (10, 35, 15, 20, 23 & 27) exhibited much larger changes in levels of intra-individual movement variability for these variables compared to their peers, thus highlighting the potential of FMP analysis to provide more specific information regarding individual movement characteristics. Mapping of normal baselines and movement boundaries for injury free athletes may also facilitate improved rehabilitation intervention if the athlete is subsequently injured (Stergiou, 2005). Therefore, whilst traditional mean group measurement and comparison is still a useful analytical tool to establish group movement trends it would be highly beneficial for future kinematic analysis to include intra-individual measurement and analyses (Chow, 2006).

FMP data could facilitate kinematic comparison and provide a realistic view of individual movement changes over time and possibly as a response to injury during differing functional tasks. This may assist identification of biomechanical changes that have real clinical relevance (Fulton, 2014). This is supported by the findings in the present study. It has been proposed previously following group comparison, that previous hamstring injury may lead to reduced ROM and velocity in the kicking hip during a kicking task (Navandar, 2017). However, no such differences were identified, following examination of the intra-individual FMPs in those individuals (participants 5, 21, 33 & 35) that experienced hamstring injuries during the present study.

Repeated individual assessment and comparison, utilising markerless motion capture instrumentation, has already been deployed in a professional sports environment in Australian Rules Football (Carltonfc.com.au, 2013). However, as yet no prior research has been undertaken that provides formal evidence to support its efficacy. Further investigation is required to explore the feasibility of employing FMP maps to monitor and identify alterations in movement behaviour and to clarify how this information could be used to inform decisions regarding future interventions. For FMPs to be successfully employed in the clinical environment, further evidence is required in the following areas: multiple FMPs need to be investigated during varied functional tasks to assess if this approach is applicable during different activities. In addition, results from

FMPs must be explored to assess efficacy for predicting changes in movement that are correlated with injury risk or that may be of benefit to guide clinical interventions.
Whilst the present research supports the capacity of an FMP type approach to identify relevant kinematic adaptations in individual movement, further investigation and clarification is needed.

6.8
Limitations With This Study & Recommendations For Future Investigation

Participant Recruitment & Assessment

The original recruitment process focused on two Singapore premier team squads, however one squad withdrew from the research immediately prior to the initial assessment and the second squad was lost to follow up after the initial assessment. The recruitment process in these instances incorporated multiple visits and discussions with the management of both teams and clear explanation of the requirements for undertaking the assessment procedures. It is difficult to provide specific recommendations that may reduce the risk of this scenario occurring in future research projects. It is possible that greater communication was required and more stringent contact and follow-up would reduce the risk of such participant loss occurring in the future. This does serve to highlight the potential difficulties associated with participant recruitment and perhaps specifically the problem of gaining access to elite level athletes due to time restraints. It also draws attention to the potential difficulties of recruitment in the team environment when gatekeeper access, in the form of the management or medical team, is required.

The initial plan for the primary research study was to undertake multiple assessments of those players who experienced injury following recovery from any subsequent injuries experienced. This would allow for repeated assessments, reducing the effect that time to assessment may have had on the kinematic results and possibly providing a more comprehensive picture of potential kinematic adaptations that occurred following injury. However, access to the participants was limited and it was the responsibility of the respective medical team to provide injury data. Due to this factor, communication issues arose and it became apparent that follow-up consultations immediately post return to play following subsequent injury would not be possible. This led to the potential for incomplete and fractured data collection and therefore the decision was made to remove the repeated assessments during the research period and to undertake just the secondary assessment at the end of the research period. This had an adverse effect on the amount of data collected and the potential for more in-depth analysis in respect to kinematic adaptation following subsequent injury. Recommendations for future research that seeks to undertake repeated measurements following subsequent injuries would be to ensure that adequate participant access is obtained and that greater control is maintained in respect to the epidemiological data collection process.

Injury Epidemiology

Kiesal et al (2007) suggest that robust injury definition should be applied when attempting to conduct research that aims to identify the efficacy of an assessment tool for injury prediction. In the present study this was achieved by implementing the OSICS injury code definitions between 59-119 (Orchard, 2010) in order to assess if an injury was appropriate to meet the injury inclusion criteria. The benefits of injury coding for specific anatomical regions has previously been demonstrated (Kramer, 1990) and these particular codes were chosen as they represent injuries in the regions that are applicable to the areas of interest for the present study (Orchard, 2010). However, due to the epidemiological data being collected from a third party source (squad physiotherapists) there are some issues with the amount of information collected. Only the region that was injured and the time span for missed training/competition was recorded and there is no specific information regarding the type of injury or structures involved. This makes it impossible to draw conclusions regarding the effect of different injury mechanisms on the data collected. Future research would benefit from more detailed and tissue specific injury description (Kiesel, 2007) to provide a more in-depth picture of injury epidemiology. A further problem is that inclusion of such a broad range of injuries in varied anatomical regions makes it problematic to clarify correlations between specific injuries and alterations in spinal kinematics. Unfortunately, narrowing the injury inclusion criteria to a specific anatomical region or injury type was impractical for the present study as it would almost certainly have required a sizable increase in sample population or lengthening of the research trial period in order to collect a suitable number of specific injuries. Whilst the present study could contribute to proof of concept in regards to general exploration of injury and regional interdependence, future studies should aim to explore the relationship between specific regions or injury types in order to further increase our understanding of the mechanisms that exist.

Considerable player injury frequencies as high as 8 to 8.5 injuries per 1000 playing hours have been reported in football (Ekstrand, 2011, Hawkins, 1999). A major risk associated with the present study was that injury occurrence, the non-manipulated independent variable, would not be sufficient during the trial period to facilitate comparative analysis. During the trial a number of participants (n = 15, 51.7%) sustained at least one injury that met the criteria for inclusion, with an average of 1.06 injuries per player. This per-player injury rate is lower than reported previously during a full playing season (Ekstrand, 2011, Hawkins, 2001). However, the present research period lasted only six months and not a full season. It is reasonable to assume that if the research period had continued for a full season, within study injury rates would have been higher and closer to those previously reported in the literature (Ekstrand, 2011, Hawkins, 2001). The injury rates reported in the present study are slightly higher than previously identified for the age groups concerned and subsequent injury rates (31%) were significantly higher than those reported previously (Bianco, 2016, Ekstrand, 2011, Hawkins, 2001). One possible explanation for the level of injury rates experienced in the present study is the effects that growth may have on injury development in participants who may not have reached full skeletal maturity (van der Sluis, 2014). However, all the participants in the present study were over 16 years of age and therefore the effect that age played in injury occurrence would have been greatly reduced (Read, 2018) In addition, it has previously been proposed that younger individuals may have the capacity to exert greater control over the multiple degrees of joint movement required to complete challenging functional tasks, thus reducing the risk of injury (Wilson, 2016). A further possibility is that the epidemiological results reported might be a consequence of higher levels of competition experienced by the participants in the present study compared to previous investigations (Faude, 2013, Kolstrup, 2016, Sreekaarini, 2014). Unfortunately it is not possible to discern the exact reason behind the higher than normal injury and re-injury levels experienced by the present research participants. Most importantly the injury rates experienced in the present study were sufficient to facilitate comparative analysis between inured and non-injured participants.

Generally increased exposure i.e. participation in training and or competition, will lead to an increased risk of injury (Ekstrand, 2011, Hawkins, 2001) and reduced training or competition will have the opposite effect (McCunn, 2016). The present study ran for approximately six months but participant training and competition exposure time was not measured or accounted for. This potentially reduces analytical power when comparing kinematic changes between groups, as it is possible that those players experiencing injury simply did so due to increased exposure time compared to their non-injured teammates. In addition, the present study did not investigate or account for previous participant injury other than the three-month injury free period that was required prior to the initial data capture session for participants to be eligible for inclusion in the research. This may adversely affect analysis of the first assessment data in respect to injury prediction (McCunn, 2016). Recommendations for future research include: increasing population size and or length of the trial period; obtaining increased participant data including prior injury history and training/competition exposure time; and narrowing the focus of kinematic analysis to individual injury types or regions. This may facilitate more in-depth analysis to be undertaken in regard to injury epidemiology and more robust investigation of the effect on spinal kinematics of specific injuries or injuries in focal anatomical regions.

Statistical issues

It must be acknowledged that there are certain inherent risks with multiple testing of data (Ranganathan, 2016) and the use of different statistical models, such as parametric and non-parametric approaches for analysing a data set (Agency, 2016). In the present study the choice of statistical method was driven by explorative findings from analysis of data distribution (Appendix 3). When more than one statistical model or analytical tool was applied to a data set e.g. mixed ANOVA and SPM analysis of the single joint variables or MAD and MAD_{es} descriptive investigation of the data, this was done to explore elements of the participant's kinematics that were not apparent using only one method. Importantly, the same significance level was maintained throughout independent of the variable assessed or the statistical model employed (Agency, 2016).

It has been suggested that application of non-linear statistical measures such as SPM is useful as it facilitates clearer interpretation of biomechanics from a spatiotemporal orientation (Pataky, 2012) and thus more information regarding the way the participant moves can be gleaned from the data. Examination of results from the present study seems to support this proposition. For example, application of a mixed ANOVA statistical test identified a significant effect of time on the lumbar flexion scores attained by the non-injured group. However, with application of SPM analysis to the same data, it was possible not only to identify a significant difference for this variable but also to pinpoint when during the task this movement variation occurred. Additionally SPM analysis of other single joint variables identified two further between-assessment variations for the non-injured participants that were significantly different; kicking hip flexion and pelvic side-bend, both of which were not identified during linear statistical analysis. Although this would seem to add strength to an argument for the superiority of non-linear statistical techniques when assessing kinematic data, it is important to note that traditional linear statistical techniques utilised in this study identified a number of statistically significant findings that were not apparent with SPM analysis. Therefore it would seem, at least for kinematic analysis of functional tasks that a combined linear and non-linear statistical approach provides the best opportunity for realising the true worth of the data collected.

An interesting observation that can be made with analysis of the intra-individual data is that there is no obvious pattern of difference between participants independent of the number of injuries experienced. Simple linear regression did identify a significant relationship between the timing of injury and the second assessment for the lumbar rotation full ROM variable. Therefore a potential difficulty with the present study is that kinematic re-measurement was not employed following each subsequent injury during the trial period. Future research could benefit from including repeated kinematic measurements of participants following recovery from each injury. This may provide a more complete picture of a participant's kinematic response to injury and the adaptations that may occur. It may also reduce the effects that the timing of injury occurrence and assessment may have on the kinematic results.

Logistic regression analysis was carried out to explore predictive relationships between the first assessment data and injury. Two variables were identified as being statistically significant in relation to injury predictive value. It is important to note that this significance occurred when the variables were analysed individually. However, logistic regression analysis of the grouped variables failed to find any significant findings. Due to the importance of this statistical test, a post hoc analysis was undertaken to measure the statistical power of the results (Faul, 2007). This analysis identified that a much larger sample size (n = 208) would be required to obtain statistical power at the recommended .80 level (Cohen, 1988). Unfortunately, the present study employed a relatively small sample size (n = 29); this was mainly a result of difficulties in gaining access to and recruiting elite level football players in Singapore. Given this small sample size extreme caution should be employed when considering the significance of the present logistic regression results in respect to injury predictive value. However, it is also valid and important to note that the sample size in the present study is larger than the vast majority of previous investigations identified in the literature that have sought to study kinematics during the football kick. (Augustus, 2017, Chow, 2006, De Witt, 2012, Fullenkamp, 2015, Inoue, 2014, Kawamoto, 2007, Kellis, 2004, Lees, 2013, Levanon, 1998, Nunome, 2002, Nunome, 2006b, Shan, 2005, Zago, 2014).

Numerical Pain Rating Scale

The present study employed a Numerical Pain Rating Scale (NPRS) (Quality, 1993) (Appendix 1) prior to data collection to assess if participants were pain free and therefore met the criteria to undertake the test protocol. The NRPS measurement tool is a tried and tested approach for the quick analysis of an individuals current pain level when applied to general populations (Downie, 1978, McCormack, 1988) and met the criteria of being relatively accurate for a broad spectrum of pain conditions and fast and easy to apply (Hawker, 2011). However, there has been limited investigation into the effectiveness of employing the NRPS for assessment of pain levels in athletic populations. In addition, it is possible that players may have not reflected the true pain levels that existed at the time of assessment. Visual analogue scales, such as the NPRS employed in this study, rely on accurate self-reporting by the participant of their pain level and there is evidence to suggest that perception of pain may differ in athletic populations. Thus there is the potential that reporting of pain may have been skewed to some degree. For example Weinberg, Vernau & Horn (2013) identified that athletes are more behaviourally inclined to continue to play when injured. Not only are athletes more inclined to continue participation when injured and in pain but they may also demonstrate higher pain tolerance particularly if they participate in contact sports

(Raudenbush, 2012). They may also exhibit relative reductions in pain perception when compared to less active members of the population (Tesarz, 2012). It is possible that these factors may have led to a reduction in the levels of pain being reported during this study. If this was the case then it is also possible that players participated in the study that were already experiencing pain due to an undiagnosed condition and that this could have compromised their kinematic movement results (Lindsay, 2002, Slaboda, 2008, Williams, 2010). Pain is a multidimensional process that affects sensory, cognitive and emotional processing (Lumley, 2011, Moriarty, 2011). Therefore a more explorative method for assessing the athlete's pain level, possibly in the form of in-depth questionnaires (Hawker, 2011) prior to undertaking the trials may have been beneficial and should be incorporated as part of the pain measurement protocol in future research.

Restriction of Movement Parameters

In the present study, in an effort to standardise the kicking position (Kellis, 2004, Opavsky, 1988, Sciuur, 2009) and to aid inter and intra-individual kinematic comparison, specific restrictions were placed on the movement parameters of participants. No run up or pre-kick step was allowed and foot placement markers were employed to standardise the initiation point of the kick and thus participant angle approach to the ball for the kicking trials. There are limitations to this approach as it may restrict elements of the participant's natural biomechanics for the kicking action by removing freedom in regards to approach speed, angle to the ball and support foot placement prior to the kick. Godik, Fales & Blashak (1993) suggest an optimum approach speed for accurate kicking with lowering of approach speed leading to reductions in kinematic velocity and increased acceleration in the hip and knee of the kicking leg (Kellis, 2004, Opavsky, 1988). In addition, there is a correlation between the last stride lengths on approach to the ball, the distance of the kick (Stoner, 1981) and the kicking power that is generated (Lees, 2002). Therefore, it is likely that preventing a run up during the data capture sessions would have had an impact on normal kicking kinematics in the present investigation. Kellis, Katis & Gissis (2004) demonstrated that changing the approach angle might alter the stance during the kick, possibly affecting balance and inducing notable kinematic change in the knee joint of the supporting leg. Stipulating the start point and thus the approach angle in the present study may have affected muscle recruitment in the supporting leg (Masuda, 2005) and could have caused significant changes in pelvic rotation and kicking hip adduction, compared to if a self-selected approach angle had been allowed (Sciuur, 2009). Even the use of a predefined target can impact kinematics (Teixeira, 1999). Lees & Nolan (2002) demonstrated reductions in pelvic, hip and knee ROM and angular velocity when kicking accuracy is the priority over maximal power. Therefore future research seeking to explore and compare inter and intra-individual kinematics during football kicking may wish to consider a design that enables data collection of the full functional activity without movement restrictions in place. It is however, valid to note that the aim of the present study was not to evaluate kinematics during the generation of long distance or high power kicks, making the previous findings regarding approach speed (Lees, 2002, Stoner, 1981) less relevant. Importantly Lees & Nolan (2002) also identified that when accurate kicking is undertaken it leads to increased movement pattern consistency of the proximal regions i.e. the trunk, pelvis and hips. The main aim of the present study was to use kicking as a functional task to facilitate investigation of kinematic changes, specifically in the proximal (spinal) region. Therefore, it was hoped that employment of a controlled target orientated kicking task would increase movement pattern consistency (Lees, 2002) and provide the optimum environment for inter and intra-individual comparative data analysis. A further factor to consider, when comparing findings from the present study to the previous literature, is that the use of footwear when kicking may reduce ball velocity by up to 1.5 per cent compared to barefoot kicking (Sterzing, 2008). In the present study, due to difficulties of using football boots in the data capture environment, participants were required to kick the ball bare foot. It may be beneficial in future investigations of kicking kinematics for the participants to wear their football boots; again this would be most relevant when investigating kicks that aim to generate maximal ball velocity. A major challenge exists for future studies that wish to investigate kicking in football and that are seeking to identify between assessments alterations in kinematics and particularly movement variability. This is the difficulty of finding the balance between reducing unwanted contributors to variation in movement during the data capture process (Godik, 1993, Kellis, 2004, Lees, 2002) whilst maintaining a kicking motion that is as close to ‘natural’ as possible.

Non-Sagittal Measurements

Prior to the principal study being started a pilot study was undertaken to investigate the capacity of the chosen motion measurement system for repeated measurements of complex functional tasks. Analysis of the pilot study data identified high Intraclass Correlation Coefficients suggesting that the equipment was fit for purpose. However, the pilot study undertaken as part of this research did not involve test-retest analysis of movements that occurred outside of the sagittal plane. It has previously been proposed that markerless motion analysis techniques may lack accuracy and reliability when measuring movements outside of the sagittal plane and specifically rotational movements in the lower limbs (Sandau, 2014, Yang, 2014). Doubts regarding the efficacy of markerless systems to capture and analyse rotational kinematics have generally been drawn following utilisation of marker-based motion analysis systems as the standard for comparison. It is valid to note that marker-based systems may also suffer inconsistencies when measuring rotational movements (Akbarshahi, 2010, Li, 2012) and therefore direct comparison between markerless and marker-based systems is problematic. There is no prior research that has investigated or sought to clarify the accuracy of markerless motion analysis systems for measuring spinal rotations or the reliability of test-retest results. Potential inaccuracies associated with the measurement and quantification of rotational movements using a markerless motion capture approach may also have led to misinterpretation of important kinematic differences that were present in the data. Therefore, it is advisable to apply caution concerning the results from the present study in respect to kinematic movements outside of the sagittal plane. Future research to investigate and clarify the accuracy and repeatability of markerless motion capture systems for measuring kinematic movements outside of the sagittal plane is recommended.

Meaningful Change

As previously highlighted, the primary aim of the pilot study in this research was to assess the capacity of the chosen motion analysis system to measure repeated assessments of a functional task. In addition, the aim of the main study was to quantify if statistical differences could be identified between injured and non-injured participants. Whilst both the pilot and main studies achieved these aims, neither study identified what constitutes meaningful change for the kinematic variables assessed. An important consideration when attempting to quantify meaningful change are the levels of intra-individual variability that occurred during the task analysed. With the levels of individual change identified, it could be argued that meaningful change should be defined at an individual level and for this to occur multiple repeated assessments would be required. This is in-line with the concept of intra-individualised profiling previously discussed in this paper.

However, the main study did identify variables, those that demonstrated statistically significant change, which could be used in future research as parameters to further investigate levels of meaningful change during this specific kicking task.

This research set out to answer and has successfully addressed a number of questions. However, as with all research, by answering questions it also highlighted further exploration that is required in order to progress our knowledge of this specific area of interest. Future studies are needed to further explore the reliability of employing markerless motion capture and analysis methods for measurements of multi-planar movement. The kinematic markers identified in this study need to be investigated in larger populations to investigate what constitutes meaningful change during different specific functional tasks and to verify correlations with aetiology. Analysis of further functional and sports specific tasks needs to be undertaken to examine which, if any kinematic markers are relevant during other types of task. In addition, if FMPs are to be more universally embraced in the sporting environment, further longitudinal studies involving a number of repeated assessments are required. These studies would also need to clarify if the information supplied by FMPs has real clinical relevance in respect to injury prevention or providing guidelines for rehabilitation post injury.

Chapter 7 Conclusion

Movement Strategy

Despite the extensive and important role it plays in football (Reilly, 2000, Yamanaka, 1997), the sub-maximal inside-of-the-foot pass kick has received limited attention in the literature (Kawamoto, 2007, Levanon, 1998, Nunome, 2002, Zago, 2014) when compared to other kicking techniques (Barfield, 1995, De Witt, 2012, Fullenkamp, 2015, Kawamoto, 2007, Kellis, 2007, Lees, 2009, Lees, 2013, Naito, 2010, Naito, 2012, Orloff, 2008). By measuring spinal, pelvic and lower extremity kinematics the present study provides the most extensive investigation carried out to date of movement properties throughout the kinematic chain during this type of kick. The present research study examined a large number of kinematic variables that form part of an extremely complex kinematic chain. From the findings it is clear that the various regions examined functioned together in a coordinated but also highly adaptable and variable manner as part of the normal motor strategy to complete the kicking task. Movement variability was present within and between individuals irrespective of injury but was also different between the injured and non-injured groups. In addition, the movement strategy employed by the players to complete the kick changed over time with notable differences between groups being identified. Also, it is possible that the movement strategies identified may change with different types of kick and when kicking the ball at different speeds as postural adjustments have been shown to be highly task specific (Beraud, 1997, Chew-Bullock, 2012).

Markerless Motion Capture

The markerless motion capture system utilised in the present research is relatively expensive, requires a fixed and controlled indoor environment in which to operate, and is unwieldy compared to some alternative motion capture systems available (Godfrey, 2008). However, it was fast, reliable and demonstrated good repeatability during the data-capture process. Data from the pilot study provides evidence that the markerless motion capture system employed (Motion) is capable of providing high levels of repeatability in respect to measuring kinematic movements to facilitate within and between assessment comparisons. In addition, the manner in which the markerless system captured movement facilitated recording of multiple participants and functional tasks in a relatively fast and user-friendly manner. This makes it ideal for the purpose of creating FMPs of multiple movement tasks for individuals and or teams. The field of biomechanical assessment would benefit greatly from the development of systems that maintain the capabilities of the present system but that are more cost effective, mobile and that are suited to less controlled environments.

Injury Prediction

Injury prediction is a complex issue and a number of factors, both intrinsic and extrinsic may contribute to the athlete being susceptible to injury (Bahr, 2005). Due to this complexity various approaches, including biomechanical (McIntosh, 2005) and epidemiological (Meeuwisse, 1994) have been proposed as possible models to aid in the injury prediction process. A four step process has been proposed (van Mechelen, 1992) for the exploration and adoption of injury prevention methods. At present, at least in the professional football environment, the first step has been achieved, that is the incidence and severity of injuries has been identified and outlined comprehensively in the literature (Ekstrand, 2011, Hawkins, 2001). In regard to the role of movement analysis as part of the injury prediction/prevention model, the sports medicine fraternity has not yet progressed beyond the second step, that is suitable identification of the underlying risk factors and injury mechanisms (van Mechelen, 1992). The present research provides some evidence that specific kinematic markers do exist and that kinematic changes in these variables may form a relationship with increased risk of injury development. In this context these characteristics, when measured with the appropriate motion analysis instrumentation may have the potential to be employed to aid injury prediction in otherwise healthy and uninjured individuals, thus progressing towards completion of the second step of injury exploration (van Mechelen, 1992). However, it is important to note that the present study also identified broad multifaceted kinematic movement variation that was present during the kicking process; independent of injury occurrence, therefore further extensive investigations are required. These investigations should explore normal and pathologically induced kinematic alterations that occur throughout varied functional and sports specific tasks in larger populations and could enhance our understanding of the kinematic factors that may contribute to increased injury risk.

Profiling Functional Movement

A strong argument has been made in the present paper to support the application of individualised measurement and analysis of kinematic movement. However, a large proportion of the statistical analysis in this research study is given over to within and between group comparisons. This was necessary as the present study is original in a number of ways. It is the first study that has attempted to apply longitudinal observations of kinematics, including movement variability, during the sub-maximal inside-of-the-foot pass kick. It is also the first study that has sought to use the data gathered from longitudinal analysis to determine if kinematics during a specific type of kick can be used to predict injury or to identify changes that may be maintained following recovery from injury. In addition, the present research analysis employed a unique approach for measuring spinal kinematics during kicking by specifically measuring lumbar and thoracic movements rather than the less specific measurement of gross trunk kinematics that has previously been employed to examine spinal kinematics during kicking (Fullenkamp, 2015, Shan, 2005). Due to this exploration of relatively uncharted waters, it was deemed necessary and important to undertake statistical group observation and analysis in addition to intra-individual analysis, in order to quantify some of the important factors held in the data and to facilitate comparison to the previous literature. However, despite the necessity in certain circumstances for group comparisons to be undertaken there is still a need to change the way we analyse and measure human movement during functional tasks in order to truly realise the potential of markerless motion capture and analysis as an injury prediction and prevention tool. It is apparent from the present research that group data may not accurately represent the movement characteristics of individual performance and that without individualised analysis, important elements of how the player completes the task may be misinterpreted or lost completely. Group comparisons may serve to provide generalised population norms and average boundaries of kinematic movement but as previously suggested are unlikely to provide data that could reliably identify individual kinematic markers of aetiological value in the clinical environment (Bahr, 2016). The findings from this study indicate that employment of individualised analysis, for example by employing FMPs, can serve to provide specific information in regards to kinematic requirements during certain functional tasks. Creation and application of individualised FMPs may facilitate measurement and analysis of individual movement characteristics and allow examination of how an athlete's movement strategy may adapt and change naturally over time or as a response to injury. This reduces the risk of important individual movement traits being lost in a plethora of group data. In addition, by identifying the individuals functional requirements for specific task completion and not simply comparing them to the 'average', we may be better equipped to develop tailored individual interventions to address alterations in kinematics if these alterations are shown to precipitate injury. However, the present study only explored one specific functional task, the sub-maximal inside-of-the-foot pass kick. Previous investigations have identified broad levels of kinematic variability during different types of football kick (Chow, 2006, Egan, 2007, Lees, 2013) during other sporting tasks (Miller, 2002, Robins, 2006, Scholz, 2000, Wilson, 2008), in occupational environments (Madeleine, 2008a, Madeleine, 2008b) and during everyday activities (Dingwell, 2006, Reisman, 2002). Therefore it is apparent that for FMPs to be effective in real world coaching and clinical environments, measurement and analysis of a number of functional tasks would need to be undertaken. This would allow a more comprehensive picture of an individual's movement strategy to be produced during different activities (Davids, 2000, Davids, 2003) and could further support the potential for applying FMPs as a tool for identifying individual movement parameters.

Adaptation & Compensatory Mechanisms

As previously discussed the real difficulty when attempting to identify compensatory mechanisms, in this case kinematic change resulting from injury, is separating within and between group changes from the alterations that naturally occur over time. The present data indicates that these normal over time adaptations are notable and occurred in both the injured and non-injured groups, posing the question, what is normal and what is pathological kinematic alteration? Quantitative differences were identified between the injured and non-injured participants. The differences highlighted may be suggestive of compensatory kinematic adaptations that occur as a result of injury and that are maintained even after pain free return to activity. Applying these findings in the clinical environment could potentially lead to more appropriate rehabilitative interventions. Nevertheless the picture is still not clear and further investigation and evidence is required before the information attained from investigations such as this study can be incorporated into the clinical setting.

The primary study undertaken in this research set out to examine three null hypotheses. Firstly, that no kinematic differences would be identified between those participants that experienced an injury during the trial and those that did not. Secondly, that the players would maintain the same kinematic strategies and therefore no significant alterations in kicking kinematics would be identified over time between the two assessments. And finally, that the kinematic movement strategy would not be altered significantly as a result of injury. Following analysis of the present data it is possible to reject all three of these null hypotheses. Definite kinematic differences were identified that differentiated those players that experienced injury from those that did not. All of the players displayed intra-individual differences in movement variability during assessments and changes in the movement strategy employed to complete the task over time. In addition, significant changes were identified for certain variables that may be present due to compensatory adaptations in movement strategy as a direct result of injury.

In sport the old adage suggests that ‘practice makes perfect’. It would seem, at least in respect to the movements required during the sub-maximal inside-of-the-foot pass kick, that ‘perfect’ might simply imply the ability of a healthy functioning system to apply diverse and changing movement strategies to complete the required sports specific goal orientated task.

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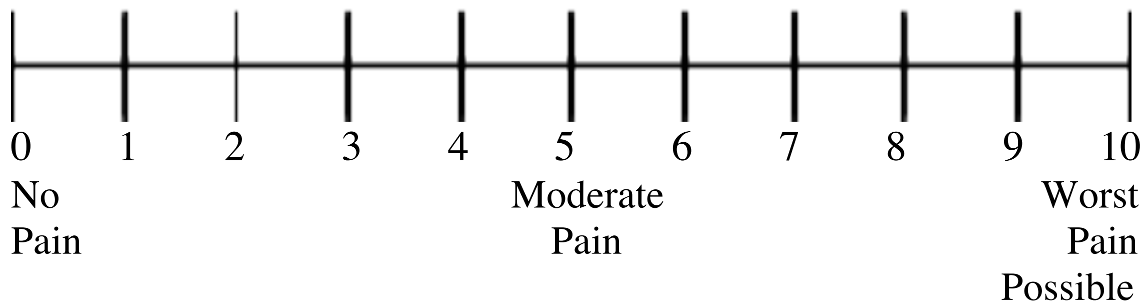
Appendix A:

Numeric Pain Scale

Patient Name:_______________________________________Date: __________

Please mark on the line on or between a number that describes your pain levels in the last 24 hours.

0-10 Numeric Pain Intensity Scale



From: Agency for Healthcare Research & Quality (Quality, 1993)

Appendix B

INFORMED CONSENT FORM

Title of Project: Do spinal kinematic changes exist in sports people who have returned to pain free activity following injury? A pre and post injury assessment of elite athletes.

Principal Researcher: Paul Bell BSc (Hon) Osteopathy

Participant's printed name:

Name:………………………………………………..……… Date:………../………/………

INTRODUCTION
We invite you to take part in a research study, which will be undertaken by Paul Bell as part of a doctoral research study program at the University of Bath (U.K). The aim is to investigate the relationship between spinal movement and injury. The assessment will be carried out at The Osteopathic Centre clinic, The Arcade, Raffles Place in Singapore. Taking part in this study is entirely voluntary. We urge you to discuss any questions about this study with Paul Bell. Talk to your family and friends about it and take your time to make your decision. If you decide to participate, you must sign this form to show that you want to take part. If you are under 18 years of age you parent or legal guardian must read and sign this consent form.
Your coach will also be consulted prior to your inclusion in this research.

Section 1. PURPOSE OF THE RESEARCH
You are being offered the opportunity to take part in this research study because you are an elite athlete, aged between 16 and 35 years of age. This research study is being undertaken to assess the possible relationship that injuries, sustained during the period of this trial, may have on spinal movement and function after the injury has healed and pain free return to activity has been achieved. It is hoped that this information may lead to improved injury prevention methods, advance rehabilitation protocols for sports competitors following injury and reduce the risks of re-injury.

Section 2. PROCEDURES
You must have read and signed this informed consent form prior to entry into the research trial. In addition, if you are under 18 years of age your parent or legal guardian must read and sign this consent form.
All participants will undertake an initial assessment protocol at the start of the trial. If you experience a lower limb, pelvic or spinal injury that prevents you from carrying out normal training or sports participation for a period of three days or more then you will be required to undertake a secondary follow-up assessment protocol within one week after full recovery. All participants, whether injured during the trial or not will undertake a last assessment at the end of the trial six months after the initial assessment. All assessments will be undertaken before any physical or skills training being undertaken on the day. The assessment involves biomechanical measurements of your body movements using a marker-less 3D motion analysis system during a sports specific functional task.

You will be required to wear close fitting clothing and your normal sports footwear. Before the test starts you will be required to complete a Numeric Pain Intensity Scale assessment to make sure you are not suffering any pain or injury and can participate in the research. The assessment will take place at the Osteopathic Centre Pte Ltd clinic, The Arcade, Raffles Place, Singapore.
You will undertake a supervised warm-up. Following the warm up you will undertake repeated repetitions of four sports specific functional tasks.

Section 3. TIME DURATON OF THE PROCEDURES AND STUDY

If you agree to take part in this study, your involvement for each assessment will last approximately twenty minutes. You will be asked to complete this assessment procedure two or three times, once at the start of the trial, once again within one week of recovery from injury and once at the end of the trial. The trial will run for a total of six months. You will be required to attend The Osteopathic Centre Pte Ltd clinic, The Arcade, Raffles Place, Singapore. Please arrive ten minutes before your assessment is scheduled to start. You will be contacted at least two weeks before your assessment to arrange a convenient time for you to attend. You will attend the assessment with at least one of your fellow players, a member of your coaching staff plus the researcher will be in attendance at all times. The assessment procedures will be undertaken at a time that does not conflict with your work or school requirements.

Section 4. DISCOMFORTS AND RISKS

You will only be allowed to take part in the assessment procedures if you are pain free at the time. The assessment involves a sports specific functional task and you will have warmed up before the assessment, so there is minimal risk of injury. However, whenever undertaking functional tasks there is always a slight risk of soft tissue injury. If you experience any pain or discomfort at any time during the assessment you must inform Paul Bell immediately and stop participation. If you experience any pain or discomfort following the assessment, please contact Paul Bell immediately.

Section 5. POTENTIAL BENEFITS

By participating in this research you will receive at least two free biomechanical analysis assessments with a market value of $360 SGD.
This research could, in the future, provide information that may reduce your risk of injury and re-injury and possibly aid in advancing injury rehabilitation techniques. In addition you will be contributing to a knowledge base that may benefit yourself and other elite athletes.

Section 6. STATEMENT OF CONFIDENTIALITY

All personal data from the trial will be anonymised and stored on a password-protected computer; this includes measurements from the sensor equipment undertaken during the assessments. Signed consent forms will be locked in a fireproof cabinet and stored within the clinic of Paul Bell, located at The Osteopathic Centre Clinic, The Arcade, Singapore. Access to data will be limited to you, Paul Bell and the research statistician.
Information may be released to your coach or physiotherapist, only if you or your parent/legal guardian give formal consent. You will, at any time, have full access to any of your personal data or information collected during the research. Data protection will meet the requirements of the United Kingdom Data Protection Act 1998 (Legislation.gov.uk, 2011) and Personal Data Protection Act 2012 of Singapore

Section 7. COSTS FOR PARTICIPATION
You will incur no costs for participation in this research

Section 8. COMPENSATION FOR PARTICIPATION
There will be no financial compensation for participation in this research.

Section 9. RESEARCH FUNDING
This research will be solely funded by Mr. Paul Bell

Section 10. VOLUNTARY PARTICIPATION
Taking part in this research study is voluntary. If you choose to take part in this research, your major responsibilities will involve participation in at least two and possibly three assessment procedures. You do not have to participate in this research. If you choose to take part you have the right to stop at any time. If you decide not to participate or if you decide to stop taking part in the research at a later date, there will be no penalty or loss of benefits to which you are otherwise entitled.
If you will be participating in another clinical trial while taking part in this research, you should discuss the procedures with Paul Bell. This precaution is intended to protect you from possible side effects from treatments or testing.

Section 11. CONTACT INFORMATION FOR QUESTIONS OR CONCERNS
You have the right to ask any questions you may have about this research. If you have questions, complaints, or concerns or believe you may have developed an injury related to this research, contact Paul Bell at [redacted] or email [redacted].

SIGNATURE AND CONSENT/PERMISSION TO BE IN THE RESEARCH

Before making the decision regarding participation in this research, you should have:
Discussed this study with the researcher, Paul Bell.
Reviewed the information in this form (with parent or legal guardian if under 18 years of age).
Had the opportunity to ask any questions you may have.
Your signature below means that you have received this information, have asked the questions you currently have about the research and have received answers to those questions. You will receive a copy of the signed and dated form to keep for future reference.
If you are under 18 years of age at the time of undertaking the assessment, your parent or legal guardian must read and sign this written consent form.

If you received this consent form by email, please print a copy and sign it if you intend to participate in the research.

Participant: By signing this consent form, you indicate that you are voluntarily choosing to take part in this research.

____________________	__________	______	_____________
Signature of Participant	Date	Time	Printed Name

Signature of Parent or Legal Guardian (If under 18 years old)	Date	Time	Printed Name

Researcher (Paul Bell): Your signature below means that you have explained the research to the participant and have answered any questions about the research.

____________________	__________	______	_____________
Signature of Researcher	Date	Time	Printed Name

Adapted from: The National Centre for Complementary and Alternative Medicine (NCCAM), Informed consent template.

Appendix C

Participant Information Sheet

Please read and sign the attached consent form (if you are under 18 years old your parent or legal guardian must also read and **sign this consent form**) prior to attending the assessment session and **bring the signed form and this sheet** with you to the assessment session.

Please complete the following details:

Name:... Date of birth.............................

Height:............................ Weight:....................

Your assessment time will be arranged by your coaching staff, please **arrive on time** - this is very important.

Please bring a tight fitting dark coloured (black or dark blue) short sleeve T-shirt and dark coloured (black or dark blue) full-length bottoms with you. Compression clothing is ideal.
If you do not have this clothing it will be supplied for you at the assessment.

Please bring dark socks with you (football socks are ideal)

If you need any further information or have any questions then you can contact Paul Bell
[redacted]
or
Balder Berckmans
Fitness Conditioning Coach / Instructor
Football Association of Singapore
[redacted]

Appendix D

Participant Script Sheets

PILOT STUDY STAND-SIT/SIT-STAND

*To be repeated to each participant immediately prior to each assessment:

Position your heels on the markers in front of the chair

For the sitting action please sit down until your bottom contacts the chair. As you sit down please bring your arms up to the front to help your balance.

Please do not sit back into the chair, once your bottom contacts the chair then immediately return to an upright standing position.

Once you have reached an upright position repeat the process.

You will be required to carry out five sit down to the chair and stand up movements. The assessor will count out each repetition during the set.

Carry out the movement at a normal comfortable speed and try to complete each repetition at the same speed.

Please practice 2 repetitions

Once you have completed 5 successful repetitions please relax and feel free to move around whilst we close down and then re-start the system.

Once the system is re-started we will repeat the whole process again.

If you experience any pain or discomfort or wish to stop the recording at any time please notify the assessor immediately.

If you have any questions please ask

Thank you

KICKING PROTOCOL

#To be repeated to each participant immediately prior to each assessment:

If you feel any discomfort or pain during the assessment procedure or wish to stop the assessment at any time please let the assessor know immediately.

You will need to hit the target 10 times to complete the assessment.

If you miss the target then we will repeat that kick.

Use the foot markers and make sure you return to the marker positions before each repetition of the kick.

The assessor will keep count of the repetitions completed

Do not attempt to kick the ball as hard as possible.

The aim is to kick the ball with enough power so it is equivalent to a five-metre pass. It is very important that you try to be as consistent with your kicks as possible, try not to vary the power of your kick.

Accuracy is important, try to hit the centre of the target.

If you have any questions please ask.

Thank you

Appendix E

Data Distribution

Maximum Scores

Tests of normality for variables assessed. Maximum ROM injured and non-injured data distribution analysis from both assessments and for each variable (injured score on top for each variable)

Tests of Normality

	Comparisons	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
RightHipFlex1		.125	15	.200	.930	15	.271
		.138	14	.200	.931	14	.317
RightHipFlex2		.166	15	.200	.935	15	.324
		.206	14	.110	.904	14	.129
HipAbd1		.123	15	.200	.966	15	.801
		.182	14	.200	.915	14	.186
HipAbd2		.113	15	.200	.968	15	.830
		.148	14	.200	.903	14	.126
KneeFLex1		.129	15	.200	.973	15	.902
		.134	14	.200	.953	14	.609
KneeFlex2		.150	15	.200	.948	15	.492
		.202	14	.128	.948	14	.535
SupKneeFlex1		.360	15	.000	.629	15	.000
		.168	14	.200	.882	14	.061
SupKneeFlex2		.187	15	.168	.861	15	.025
		.179	14	.200	.898	14	.104
PelvicSideBend /1		.200	15	.108	.834	15	.010
		.130	14	.200	.916	14	.192
PelvicSideBend /2		.174	15	.200	.881	15	.050
		.124	14	.200	.956	14	.653
PelRot1RIGHT		.122	15	.200	.964	15	.769
		.200	14	.136	.889	14	.079
PelRot2RIGHT		.236	15	.024	.911	15	.142
		.196	14	.152	.951	14	.576
LumbarFlex /1		.146	15	.200	.922	15	.209
		.164	14	.200	.916	14	.191
LumbarFlex /2		.149	15	.200	.913	15	.152
		.162	14	.200	.922	14	.237
LumbarRotation /1		.358	15	.000	.565	15	.000
		.113	14	.200	.969	14	.858
LumbarRotation /2		.256	15	.009	.763	15	.001
		.163	14	.200	.941	14	.437

Tests of Normality							
		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Comparisons	Statistic	df	Sig.	Statistic	df	Sig.
LumbarLateralFlex /1RIGHT		.160	15	.200	.935	15	.319
		.176	14	.200	.905	14	.132
LumbarLateralFlex /2RIGHT		.199	15	.114	.886	15	.057
		.240	14	.028	.912	14	.170
ThorFlex1		.178	15	.200	.927	15	.247
		.136	14	.200	.946	14	.504
ThorFlex2		.134	15	.200	.947	15	.474
		.202	14	.127	.858	14	.028
ThorRot1		.306	15	.001	.701	15	.000
		.159	14	.200	.954	14	.619
ThorRot2		.245	15	.015	.877	15	.043
		.160	14	.200	.955	14	.646
ThoLatFlex1RIGHT		.186	15	.173	.869	15	.033
		.131	14	.200	.920	14	.218
ThorLatFlex2RIGHT		.167	15	.200	.946	15	.468
		.243	14	.025	.795	14	.004
LumbarAngVelocity /1		.134	15	.200	.955	15	.602
		.161	14	.200	.946	14	.502
LumbarAngVelocity /2		.160	15	.200	.917	15	.172
		.193	14	.167	.949	14	.543
ThorAngVel1		.157	15	.200	.921	15	.197
		.375	14	.000	.552	14	.000
ThorAngVel2		.170	15	.200	.922	15	.203
		.193	14	.166	.923	14	.241
PelRotVel1		.190	15	.148	.923	15	.214
		.176	14	.200	.950	14	.568
PelROtVel2		.145	15	.200	.952	15	.551
		.182	14	.200	.937	14	.385
KickHipVel1		.168	15	.200	.978	15	.955
		.212	14	.087	.886	14	.071
KickHipVel2		.130	15	.200	.937	15	.348
		.255	14	.014	.877	14	.052
FootVel1		.184	15	.183	.942	15	.409
		.171	14	.200	.883	14	.064
FootVEl2		.104	15	.200	.964	15	.759
		.199	14	.138	.904	14	.128
COMDisp1		.126	15	.200	.972	15	.883
		.249	14	.019	.852	14	.024
COMDisp2		.188	15	.160	.954	15	.595
		.143	14	.200	.914	14	.183
COMX1		.194	15	.135	.933	15	.298
		.208	14	.103	.920	14	.219
COMX2		.303	15	.001	.831	15	.009
		.129	14	.200	.968	14	.852

a. Lilliefors Significance Correction

Full ROM

Test of normaility for full ROM injured and non-injured data distribution analysis from both assessments and for each variable.

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	InjNonInj	Statistic	df	Sig.	Statistic	df	Sig.
1	Injured	.183	15	.186	.905	15	.114
	Non-Injured	.113	14	.200*	.973	14	.916
RightHipFlex2	Injured	.106	15	.200*	.973	15	.902
	Non-Injured	.154	14	.200*	.958	14	.692
HipAbd1	Injured	.115	15	.200*	.974	15	.913
	Non-Injured	.187	14	.200*	.948	14	.531
HipAbd2	Injured	.110	15	.200*	.975	15	.919
	Non-Injured	.111	14	.200*	.954	14	.629
KneeFLex1	Injured	.154	15	.200*	.960	15	.685
	Non-Injured	.124	14	.200*	.964	14	.786
KneeFlex2	Injured	.103	15	.200*	.975	15	.928
	Non-Injured	.119	14	.200*	.981	14	.980
SupKneeFlex1	Injured	.351	15	.000	.681	15	.000
	Non-Injured	.124	14	.200*	.965	14	.800
SupKneeFlex2	Injured	.198	15	.117	.834	15	.010
	Non-Injured	.179	14	.200*	.923	14	.242
PelvicSideBend1	Injured	.132	15	.200*	.951	15	.535
	Non-Injured	.134	14	.200*	.961	14	.744
PelvicSideBend2	Injured	.120	15	.200*	.978	15	.956
	Non-Injured	.229	14	.044	.853	14	.024
PelRot1Max	Injured	.166	15	.200*	.929	15	.260
	Non-Injured	.145	14	.200*	.974	14	.929
PelRot2Max	Injured	.162	15	.200*	.945	15	.452
	Non-Injured	.206	14	.111	.915	14	.185
LumbarFlex1	Injured	.204	15	.095	.885	15	.057
	Non-Injured	.124	14	.200*	.955	14	.636
LumbarFlex2	Injured	.159	15	.200*	.974	15	.908
	Non-Injured	.123	14	.200*	.976	14	.945
LumbarRotation1	Injured	.203	15	.098	.870	15	.034
	Non-Injured	.163	14	.200*	.917	14	.198
LumbarRotation2	Injured	.125	15	.200*	.954	15	.595
	Non-Injured	.171	14	.200*	.928	14	.289

LumbarLateralFlex1MAX		.123	15	.200	.975	15	.919
		.154	14	.200	.957	14	.668
LumbarLateralFlex2MAX		.107	15	.200	.977	15	.940
		.145	14	.200	.969	14	.868
ThorFlex1		.183	15	.187	.942	15	.409
		.173	14	.200	.938	14	.390
ThorFlex2		.214	15	.062	.916	15	.168
		.186	14	.200	.851	14	.023
ThorRot1		.148	15	.200	.925	15	.228
		.275	14	.005	.769	14	.002
ThorRot2		.154	15	.200	.841	15	.013
		.137	14	.200	.901	14	.116
ThoLatFlex1Max		.099	15	.200	.979	15	.962
		.121	14	.200	.966	14	.816
ThorLatFlex2MAX		.115	15	.200	.962	15	.729
		.141	14	.200	.969	14	.865
ComY1		.210	15	.073	.838	15	.012
		.120	14	.200	.987	14	.997
ComY2		.127	15	.200	.963	15	.739
		.131	14	.200	.934	14	.351
COMX1		.151	15	.200	.929	15	.265
		.163	14	.200	.855	14	.026
ComX2		.285	15	.002	.838	15	.012
		.214	14	.081	.917	14	.197
COMDisp1		.133	15	.200	.964	15	.760
		.257	14	.013	.892	14	.086
COMDisp2		.129	15	.200	.968	15	.829
		.220	14	.065	.877	14	.053

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Appendix F

Participant Injury Epidemiology

Epidemiological data including participant number, playing position, dominant kicking leg, date of injury/injuries, region affected and total training/competition time lost due to the injury

Participant Number & Position	Dominant Leg	DATE INJ 1	Region Injured	Days Lost	DATE INJ 2	Region Injured	Days Lost	DATE INJ 3	Region Injured	Days Lost	DATE INJ 4	Region Injured	Days Lost	DATE INJ 5	Region Injured	Days Lost
P3 Striker	R		Foot	**4**	08/07	Lower back	**11**									
P4 Defender	R	29/08	Groin	**4**	09/11	Groin	**7**									
P5 Goal keeper	R	19/05	Hamstring	**3**												
P6 Defender	L	20/05	Groin	**3**	07/07	Low back	**2**	28/07	Low leg	**3**	27/08	Thigh	**2**	22/09	Groin	**3**
P10 Midfield	R	06/02	Toe	**6**	17/08	Thigh	**3**									
P16 Winger	R	03/06	Knee	**30**	14/08	Low leg	**2**									
P17 Midfield	R	23/05	Knee	**30**												
P18 Midfield	R	21/08	Thigh	**2**	24/08	Ankle	**2**	27/08	Thigh	**7**	16/10	Ankle	**14**			
P21 Wing back	R	24/08	Thigh	**2**	22/10	Hamstring	**2**									

P25 Midfield	R	28/07	Achilles Tendon	**11**	08/10	Thigh	**11**	10/03	Ankle	**5**						
P26 Defender	R	02/10	Foot	**30**												
P33 Midfield	R	14/08	Hamstring	**4**												
P35 Defender	R	03/06	Low leg	**2**	11/07	Low Leg	**21**	08/10	Hamstring	**4**						
P36 Defender	R	03/06	Groin	**2**												
P40 Midfield	R	11/10	Ankle	**14**												

Appendix G

SPM Analysis –Significant & Non-Significant but Notable Findings

Non-injured group between assessment significant findings

SPM analysis

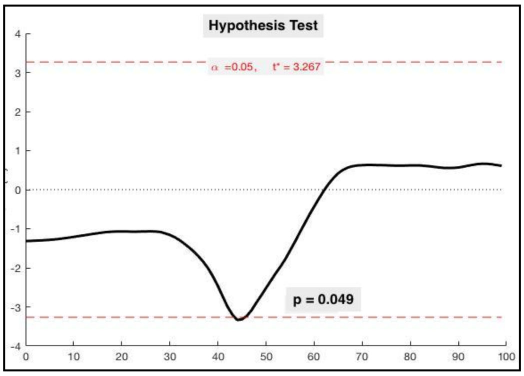


Figure G1: Kicking hip flexion

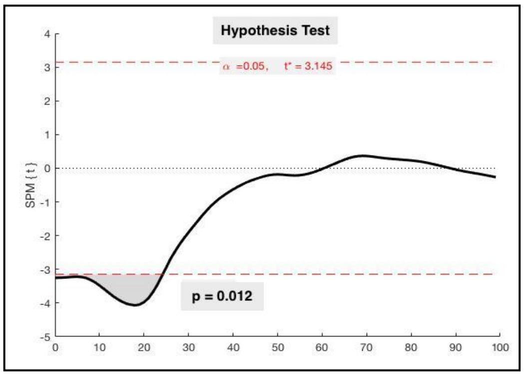


Figure G2: Pelvic side bend

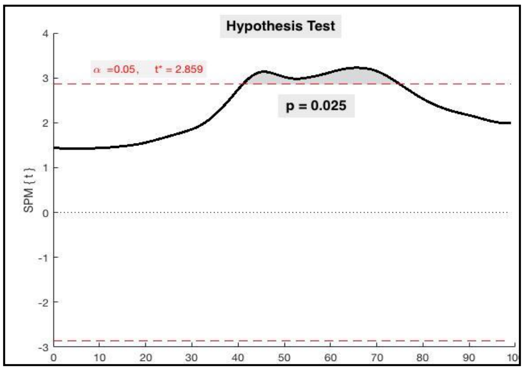


Figure G3: Lumbar flexion

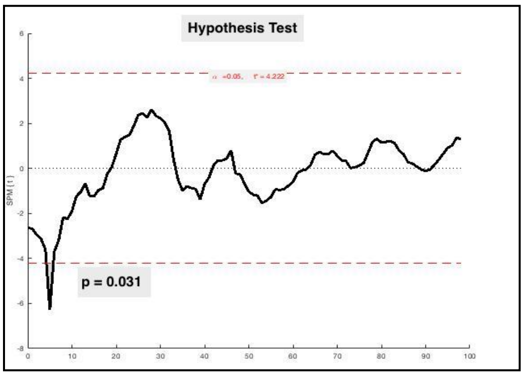


Figure G4: Pelvic rotation-Thoracic rotation

Figure G1: Kicking hip flexion critical threshold exceeded at 44-46%, p = 0.049
Figure G2: Pelvic side-bend critical threshold exceeded at 8-25%, p = 0.012
Figure G3: Kicking hip flexion critical threshold exceeded at 40-75%, p = 0.025
Figure G1: Pelvic rotation-Thoracic rotation critical threshold exceeded at 3-7%, p = 0.031

Non-significant but notable between group first assessment findings

SPM analysis

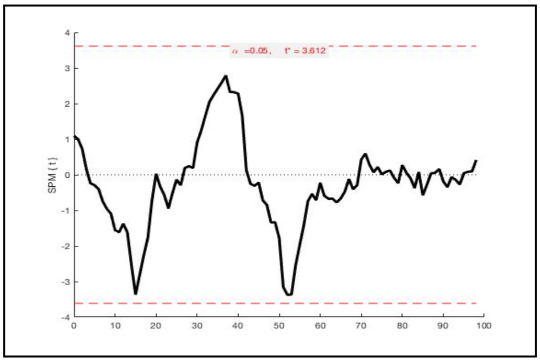


Figure G5: Kicking knee flexion-Thoracic rotation

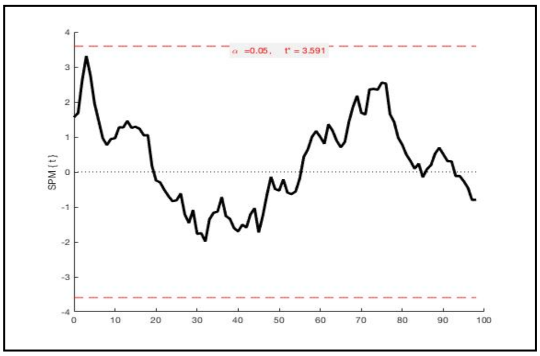


Figure G6: Kicking hip flexion-Lumbar rotation

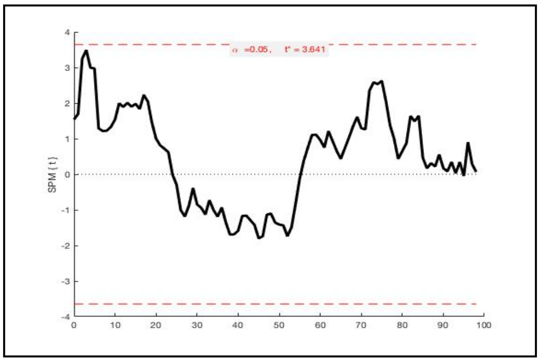


Figure G7: Kicking hip flexion-Pelvic rotation

SPM between groups first assessment comparison of coupled angles. Non-significant but notable between group differences for Kicking knee flexion-Thoracic rotation (Figure G5) at 15% and 53%, Kicking hip flexion-Lumbar rotation (Figure G6) at 3% and Kicking hip flexion-Pelvic rotation (Figure G7) at 3%.

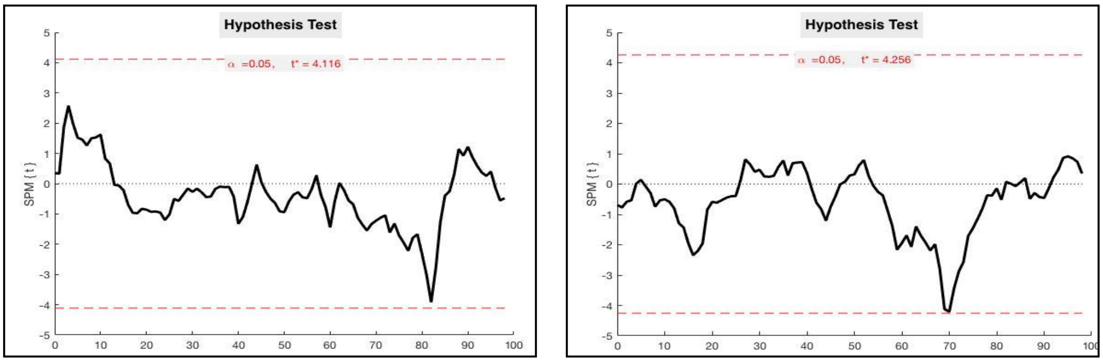


Figure G8 & G9: First assessment between groups comparison of coupled angles. Non-significant but notable between groups difference for Kicking hip flexion-Thoracic lateral flexion at 83% and 70% in the injured and non injured groups respectively.

Appendix H

Group MAD_{es} & MAD Tables Full & Maximum ROM

Full ROM Scores

Table I1: Full ROM MAD_{es} between group values during assessment 1 and 2 and within group values between assessments

MAD effect size Full ROM scores	***$_i$MAD Injured+Non-injured 1***	***$_i$MAD Injured+ Non-injured 2***	***$_d$MAD Injured 1-2***	***$_d$MAD Non-injured 1-2***
RightHipFlex	-0.04	0.16	0.04	0.25
HipAbd	-0.03	0.37	-0.01	0.39
KneeFlex	-0.44	-0.49	0.02	-0.05
SupKneeFlex	-0.08	0.16	-0.19	0.05
PelvicSideBend	0.32	0.52	0.02	0.20
PelRot	0.26	0.47	-0.35	-0.12
LumbarFlex	-0.17	0.08	0.00	0.26
LumbarRotation	0.03	0.61	0.37	1.02
LumbarLateralFlex	0.75	0.65	0.27	0.13
ThorFlex	-0.16	-0.32	0.81	0.88
ThorRot	1.00	1.79	0.05	0.70
ThorLatFle	0.43	0.49	0.38	0.42
LumbarAngVelocity	-0.23	0.53	-0.23	0.53
ThorAngVel	0.35	0.16	0.47	0.30
PelROtVel	-0.10	0.47	-0.15	0.42
KickHipVel	-0.49	0.28	0.39	1.40
FootVEl	-0.33	-0.39	0.49	0.51
COMDisp	-0.13	0.00	-0.02	0.10
ComX	-0.28	0.00	-0.07	0.20
HipFlex-LspRot	0.12	0.09	-0.21	-0.22
PelSideBend-LspRot	0.12	-0.34	0.21	-0.24
SupKneeFlex-PelSideBend	0.68	0.12	0.69	0.13
HipFlex-PelRot	0.09	0.02	-0.05	-0.12

KneeFlex-ThorRot	0.00	0.10	-0.08	0.03
HipFlex-ThorLatFlex	0.02	-0.03	-0.08	-0.12
HipFlex-ThorRot	0.10	0.00	-0.07	-0.16
PelRot-ThorRot	0.32	-0.19	0.53	0.03
HipFlex-LspFlex	0.11	0.06	-0.16	-0.19
PelSideBend-ThorRot	-0.21	-0.15	0.10	0.15
	Negative score = Assessment mean non-injured > injured		Negative score = Assessment Mean 2nd assessment > 1st	

TableI2: Full ROM ***MAD*** group value during assessment 1 and 2

MAD Full ROM	***Injured-1***	***Injured- 2***	***Non-Injured 1***	***Non-Injured 2***
RightHipFlex	*21.24*	*20.32*	*21.13*	*19.47*
HipAbd	*15.50*	*15.73*	*15.85*	*13.67*
KneeFlex	*16.56*	*17.26*	*19.89*	*20.77*
SupKneeFlex	*7.58*	*7.94*	*7.01*	*6.66*
PelvicSideBend	*7.66*	*7.66*	*7.20*	*6.53*
PelRot	*10.57*	*11.71*	*10.23*	*9.94*
LumbarFlex	*2.83*	*2.79*	*2.95*	*2.67*
LumbarRotation	*2.76*	*2.34*	*2.61*	*2.09*
LumbarLateralFlex	*3.98*	*3.62*	*3.25*	*3.02*
ThorFlex	*6.62*	*5.38*	*6.96*	*5.57*
ThorRot	*3.25*	*3.13*	*2.20*	*1.64*
ThorLatFlex	*15.82*	*13.70*	*15.02*	*12.84*
COMDisp	*0.020*	*0.021*	*0.018*	*0.019*
ComX	*0.014*	*0.014*	*0.012*	*0.013*
HipFlex-LspRot	*14.53*	*16.86*	*15.60*	*15.51*
PelSideBend-LspRot	*11.78*	*10.56*	*12.79*	*13.19*
SupKneeFlex-PelSideBend	*10.68*	*11.41*	*12.80*	*13.83*
HipFlex-PelRot	*14.03*	*13.66*	*15.16*	*14.15*
KneeFlex-ThorRot	*15.31*	*16.71*	*17.03*	*19.90*
HipFlex-ThorLatFlex	*11.08*	*12.15*	*12.39*	*12.36*
HipFlex-ThorRot	*14.22*	*15.38*	*15.49*	*15.85*

PelRot-ThorRot	*15.73*	*14.04*	*14.54*	*14.15*
HipFlex-LspFlex	*15.04*	*17.03*	*16.03*	*17.01*
PelSideBend-ThorRot	*13.13*	*13.40*	*13.09*	*13.22*

Maximum ROM Scores

Table I3: Maximum ROM score MAD effect size between group values for assessment 1 and 2 and within group values between assessments.

MAD effect size Maximum ROM scores	***$_i$MAD Injured+Non -injured 1***	***$_i$MAD Injured+ Non-injured 2***	***$_d$MAD Injured 1-2***	***$_d$MAD Non-injured 1-2***
RightHipFlex	-0.13	-0.12	0.03	0.05
HipAbd	-0.09	0.32	0.03	0.38
KneeFlex	-0.24	-0.26	-0.02	-0.07
SupKneeFlex	-0.04	-0.13	0.00	-0.11
PelvicSideBend	0.21	0.07	0.04	-0.12
PelRot	-0.03	0.05	-0.08	0.01
LumbarFlex	-0.34	0.03	-0.06	0.29
LumbarRotation	-0.17	0.16	-0.11	0.26
LumbarLateralFlex	0.71	0.37	0.27	0.00
ThorFlex	-0.19	-0.22	0.31	0.30
ThorRot	-0.18	0.20	-0.36	-0.01
ThorLatFle	0.21	0.10	0.11	0.02
LumbarAngVelocity	-0.04	0.25	-0.08	0.22
ThorAngVel	0.22	0.09	0.24	0.10
PelROtVel	0.02	0.24	-0.04	0.19
KickHipVel	-0.01	0.11	0.18	0.28
FootVEl	-0.06	0.03	0.20	0.27
COMDisp	0.12	0.13	0.02	0.03
ComX	-0.05	0.00	-0.01	0.04
	Negative score = Assessment mean non-injured > injured		Negative score = Assessment Mean 2nd assessment > 1st	

Table I4: Maximum ROM ***MAD g***roup value during assessment 1 and 2

MAD ***Maximum ROM***	***Injured-1***	***Injured- 2***	***Non-Injured 1***	***Non-Injured 2***
RightHipFlex	26.89	23.54	29.80	29.21
HipAbd	14.04	15.61	18.85	17.54
KneeFlex	35.07	39.02	39.05	44.17
SupKneeFlex	21.21	22.95	22.97	26.13
PelvicSideBend	8.93	8.26	8.45	4.41
PelRot	14.63	15.76	15.69	18.16
LumbarFlex	8.54	8.04	9.08	7.72
LumbarRotation	3.89	4.21	2.71	2.96
LumbarLateralFlex	6.61	5.75	3.94	5.05
ThorFlex	30.36	27.02	27.47	32.44
ThorRot	14.44	13.21	12.35	14.19
ThorLatFlex	16.83	17.56	13.01	12.91
LumbarAngVelocity	109.16	109.29	95.94	100.59
ThorAngVel	82.18	73.64	83.39	72.72
PelROtVel	125.92	129.60	111.30	111.08
KickHipVel	0.82	0.79	0.85	0.67
FootVEl	4.13	3.76	4.41	3.84
COMDisp	0.11	0.11	0.11	0.12
ComX	0.04	0.04	0.05	0.05

Appendix I

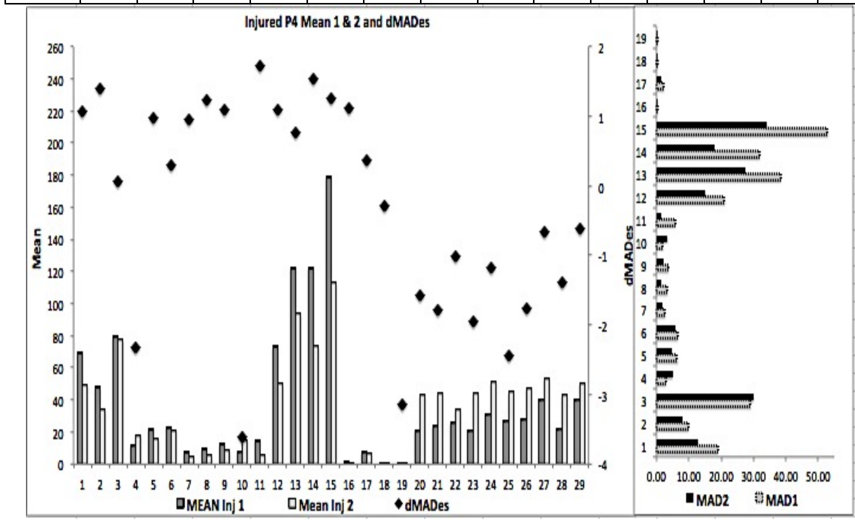
Intra-Individual Functional Movement Profile Graphs: Injured & Non-Injured

Injured

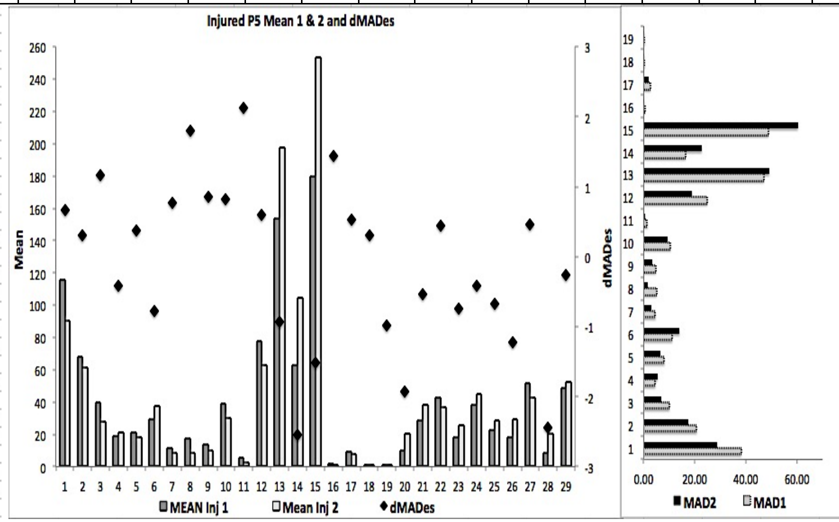
Participant intra-individual full ROM mean score for both assessments and between assessments $dMAD_{es}$ for all of the variables assessed (n = 29). In addition, the intraindividual MAD during both assessments for the discrete variables assessed (n = 19). *Negative effect sizes indicate larger mean scores in the second assessment

Horizontal axis for mean and $dMAD_{es}$ variable scores (1-29). Vertical axis for MAD variable scores (1-19)

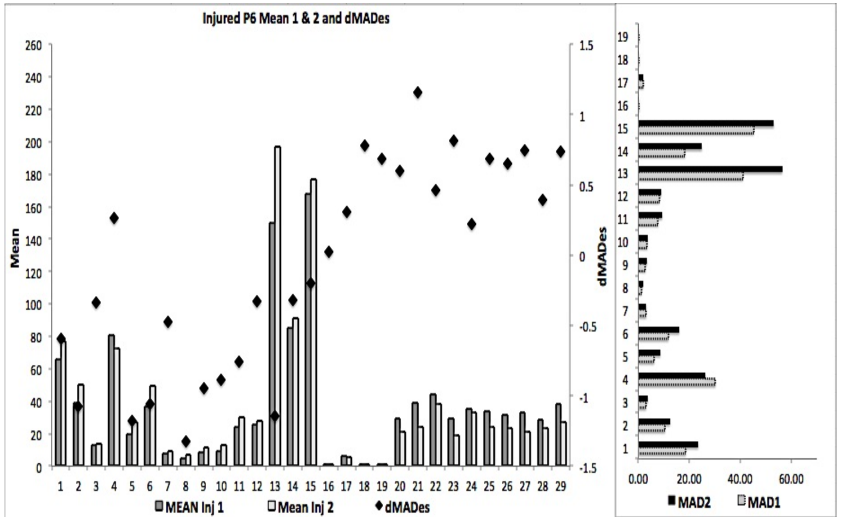
Variable	RightHippFlexion	HipAbduction	KneeFlexion	SupKneeFlexion	PelvicSideBend	PelRotation	LumbarFlexion	LumbarRotation	LumbarLateralFlexion	ThorFlexion	ThorRotation	ThorLatFlexion	LumbarAngularVelocity	ThoracicAngularVelocity	PelvicRotationalVelocity	KickHipVelocity	FootVelocity	COMDisp	ComX	HipFlex-LspRoation	PelSideBend-LspRot	SupKneeFlex-PelSideBend	HipFlex-PelRot	KneeFlex-ThorRot	HipFlex-ThorLatFlex	HipFlex-ThorRot	PelRot-ThorRot	HipFlex-LspFlex	PelSideBend-ThorRot
Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29



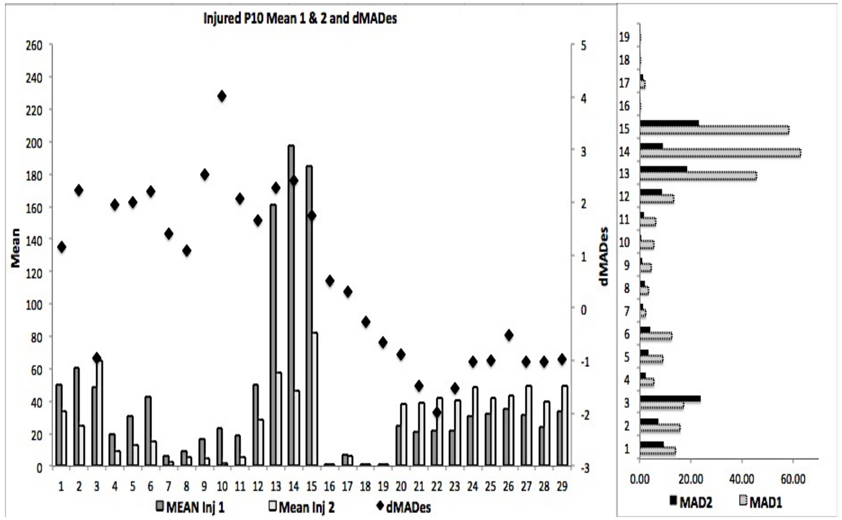
Participant 4



Participant 5



Participant 6



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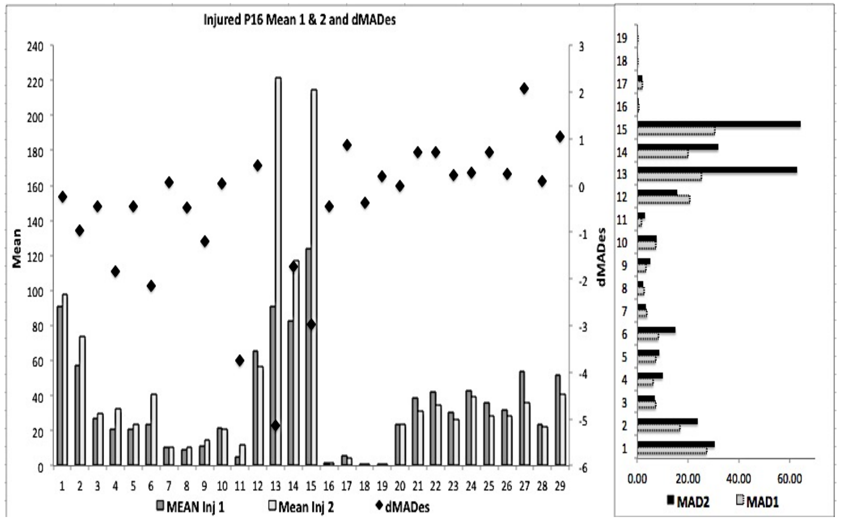

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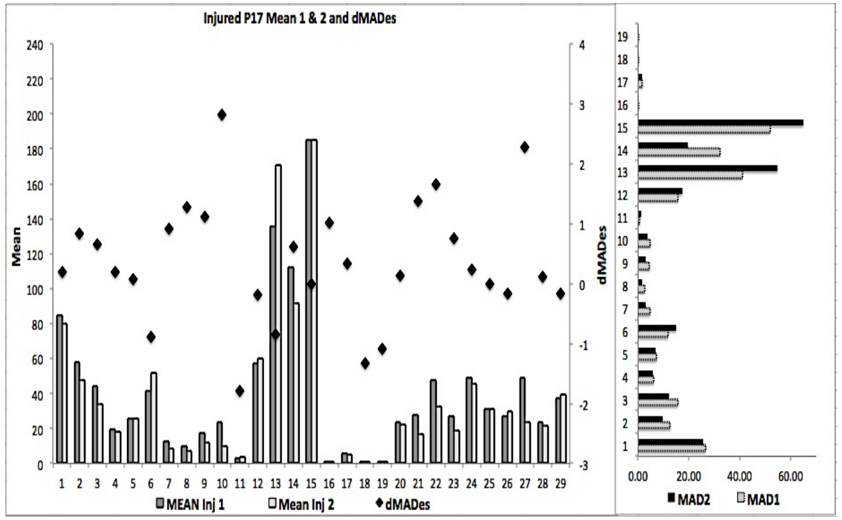

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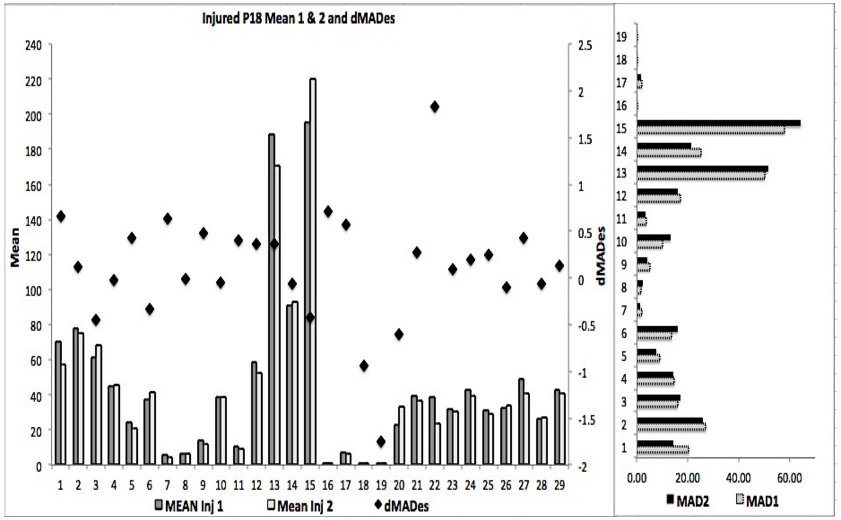

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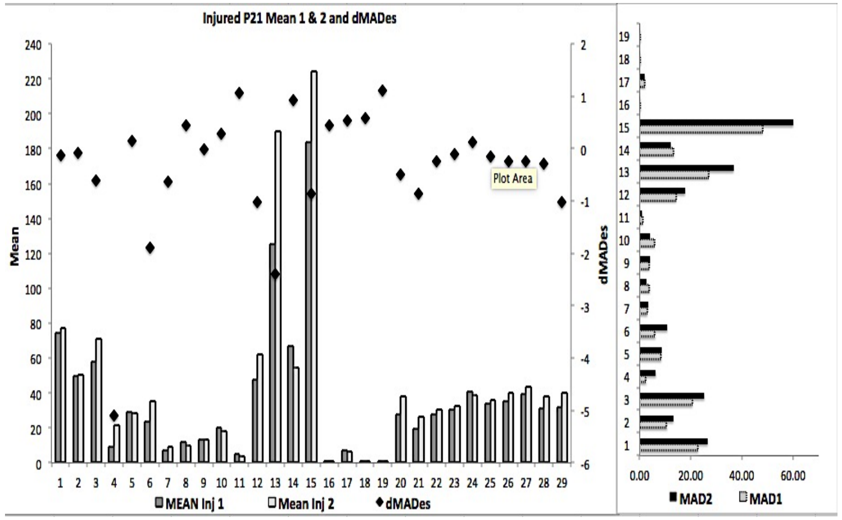

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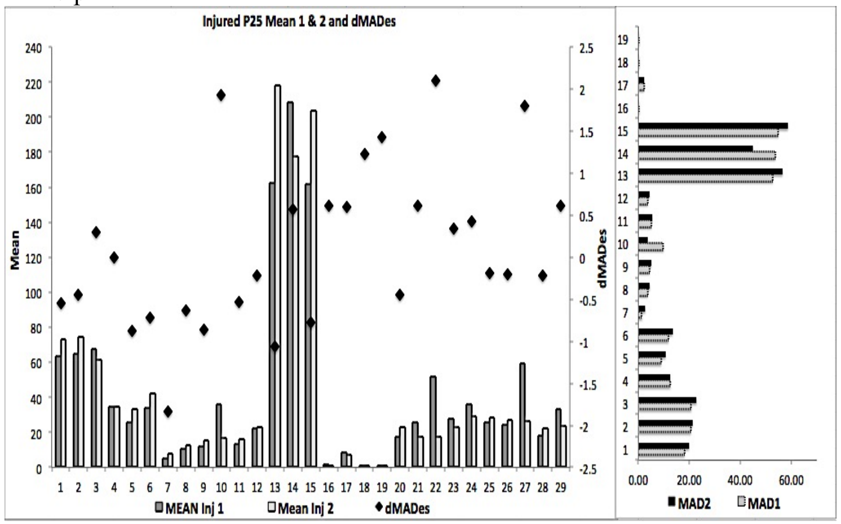

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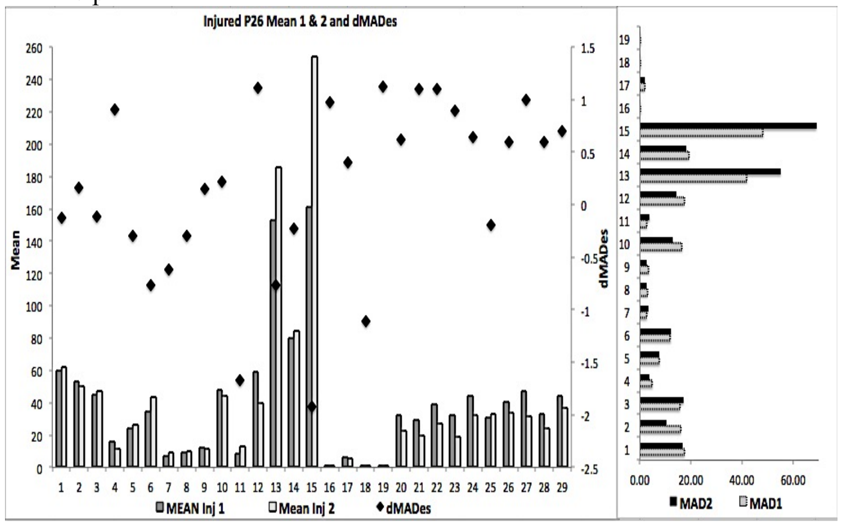

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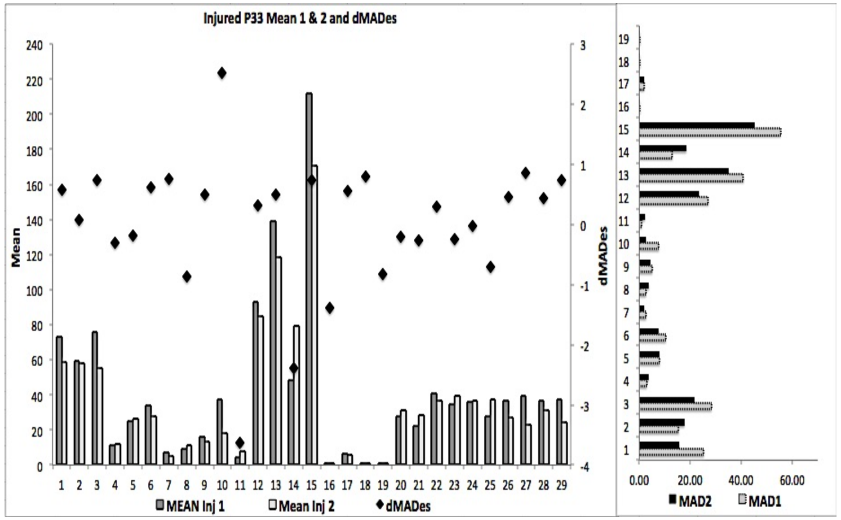

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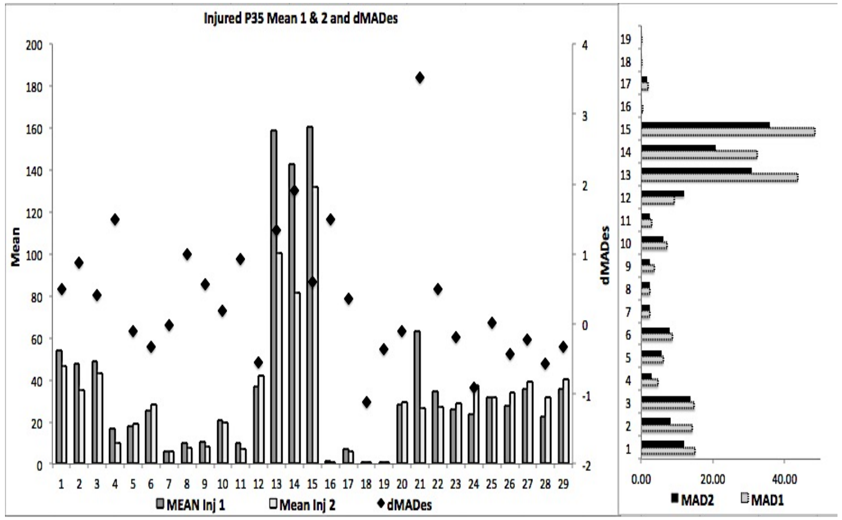

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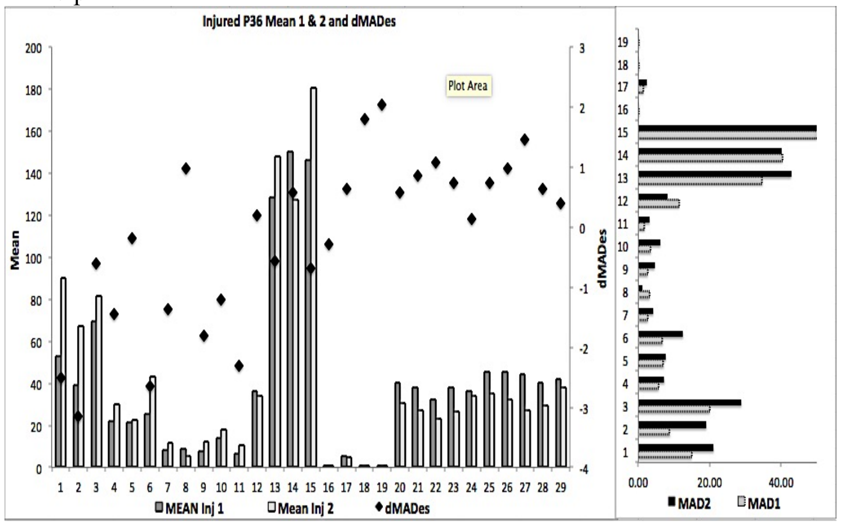

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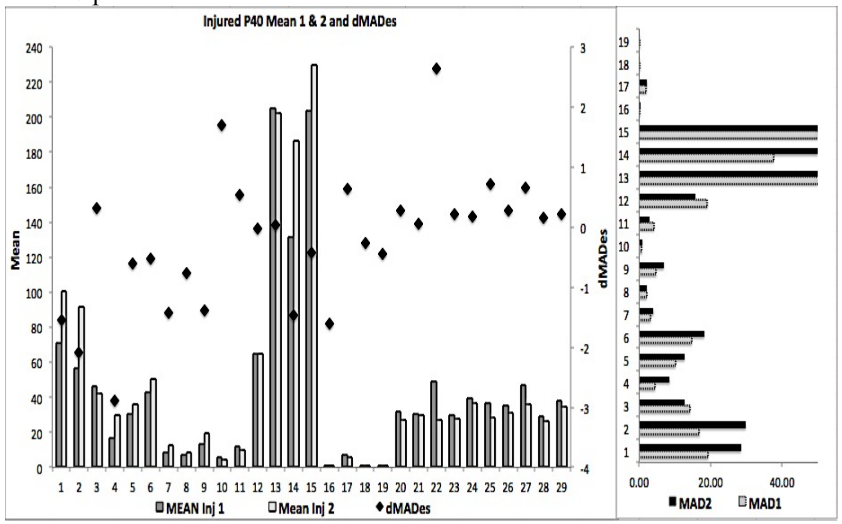
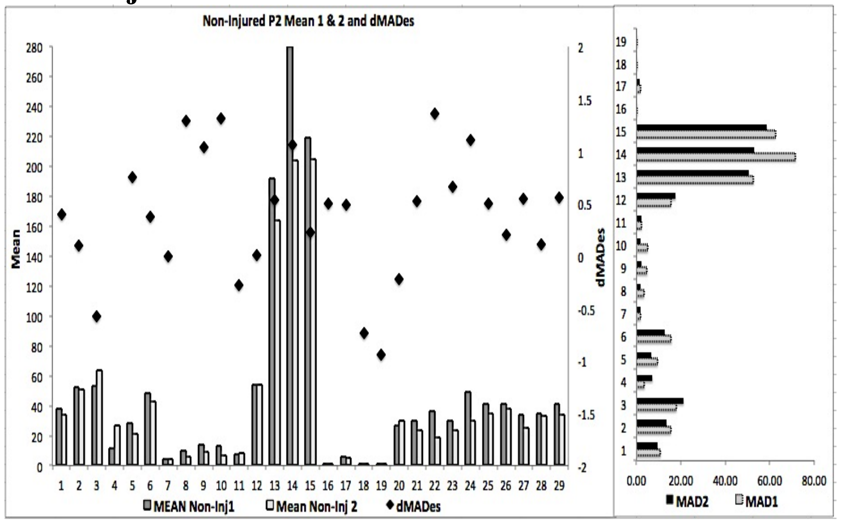


Participant 40

Intra-Individual Graphs

Non-Injured



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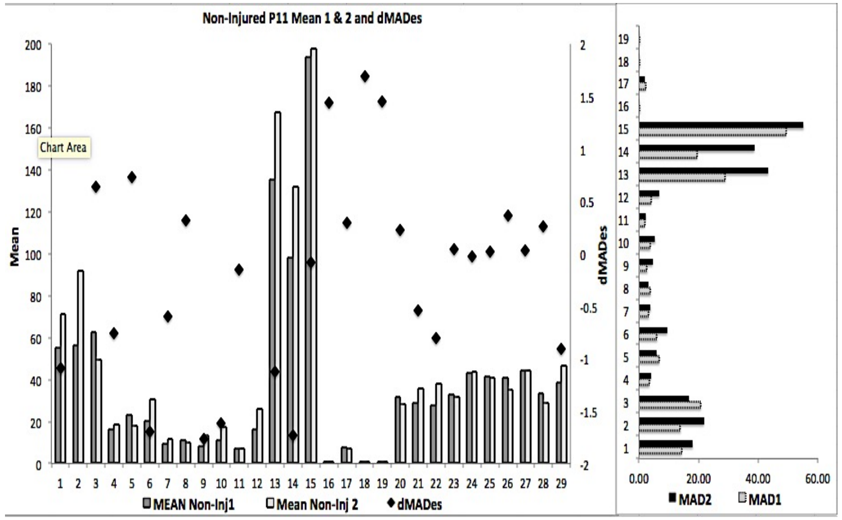

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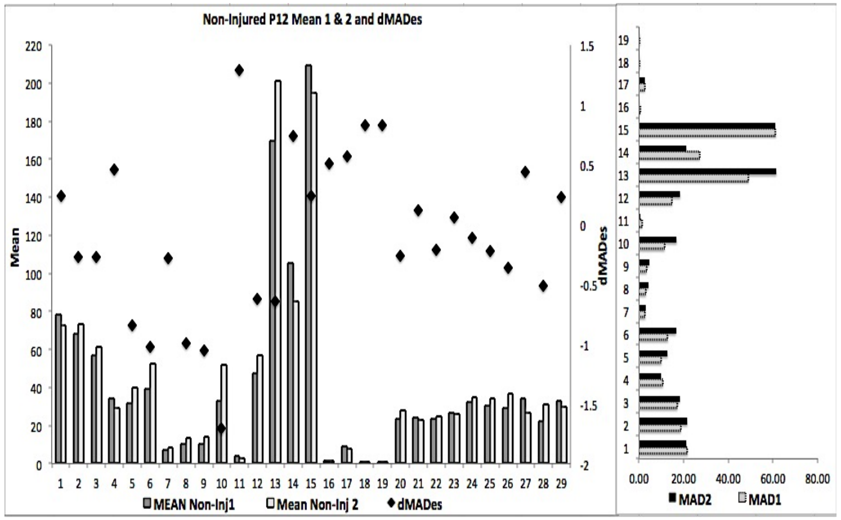

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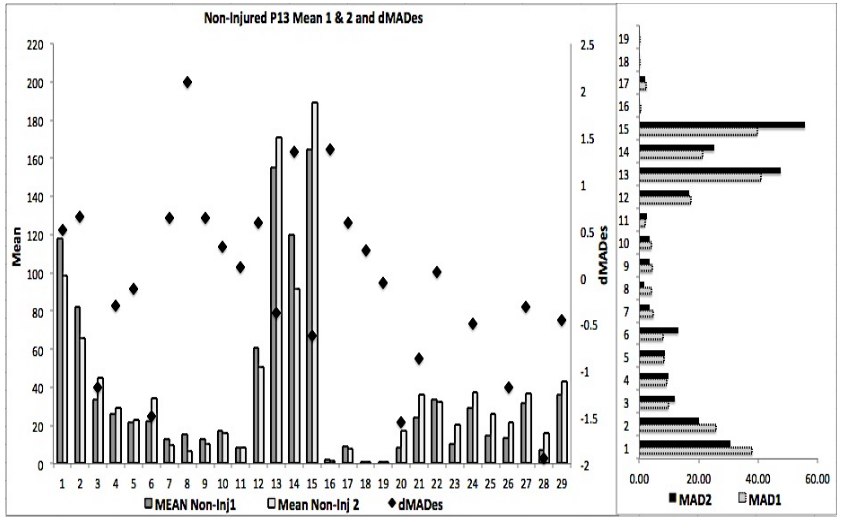

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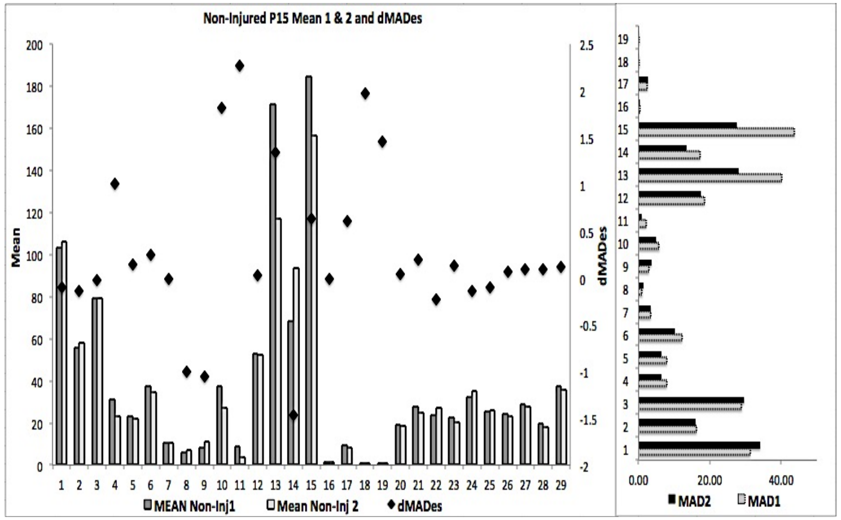

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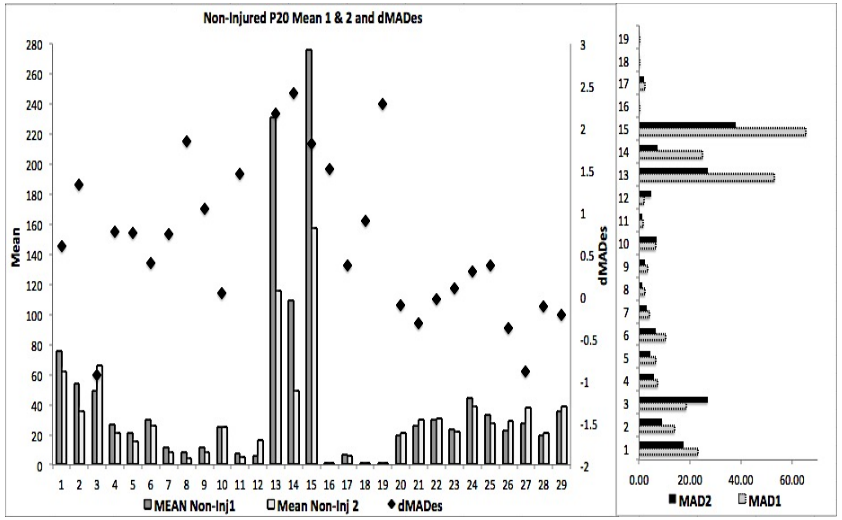

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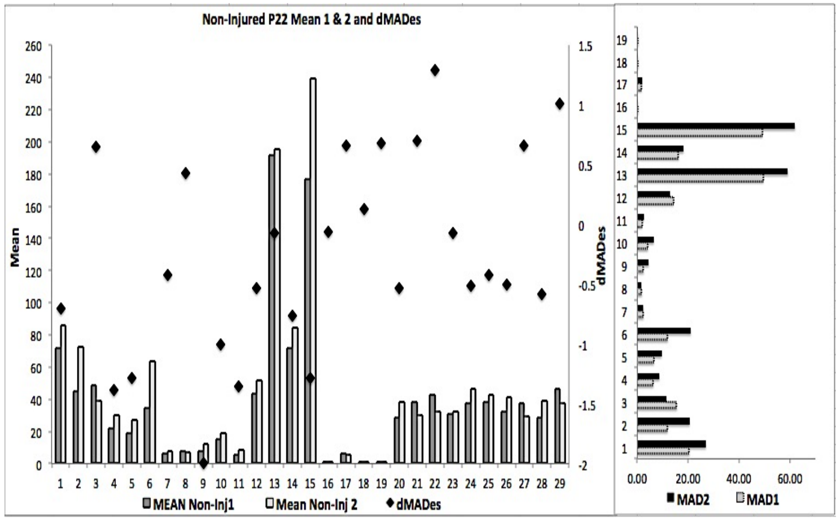

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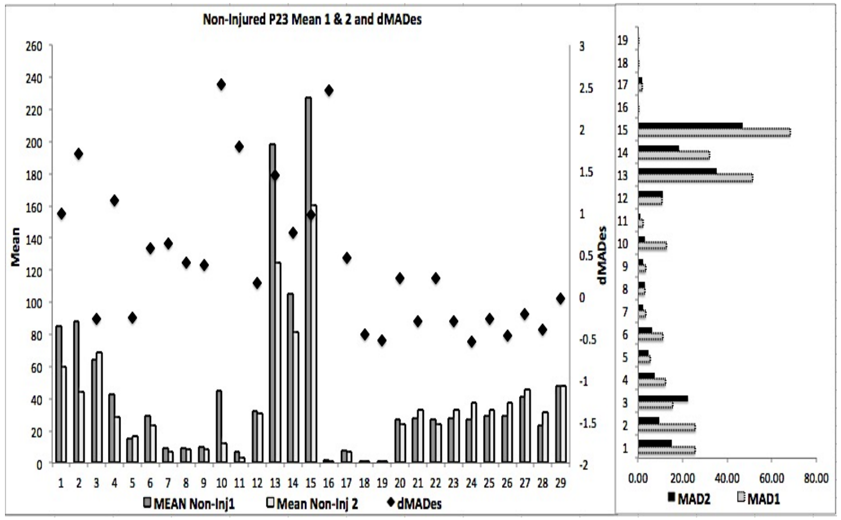

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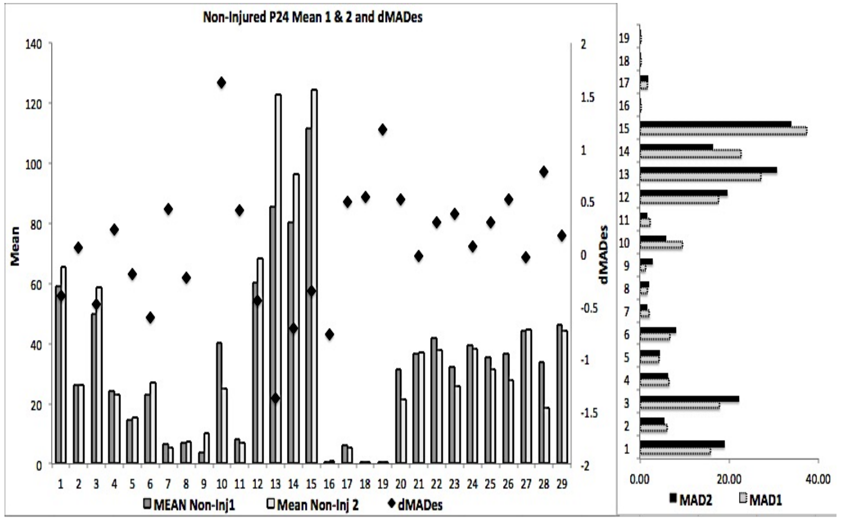

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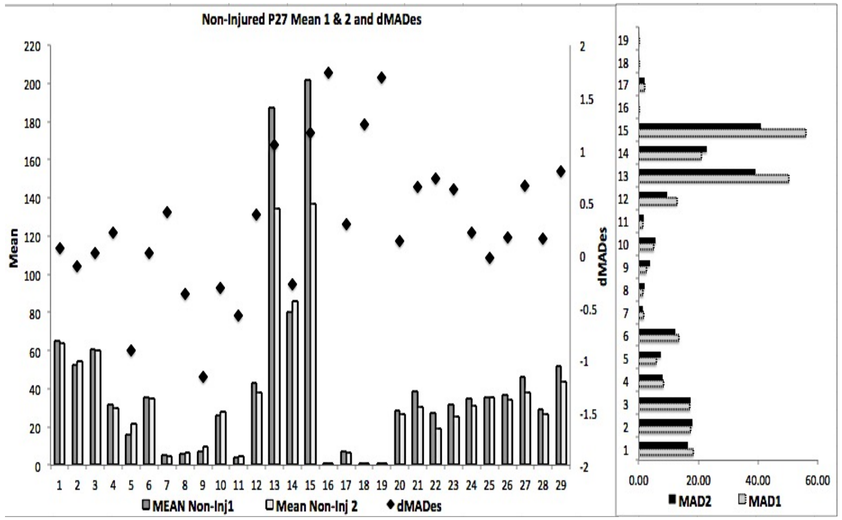

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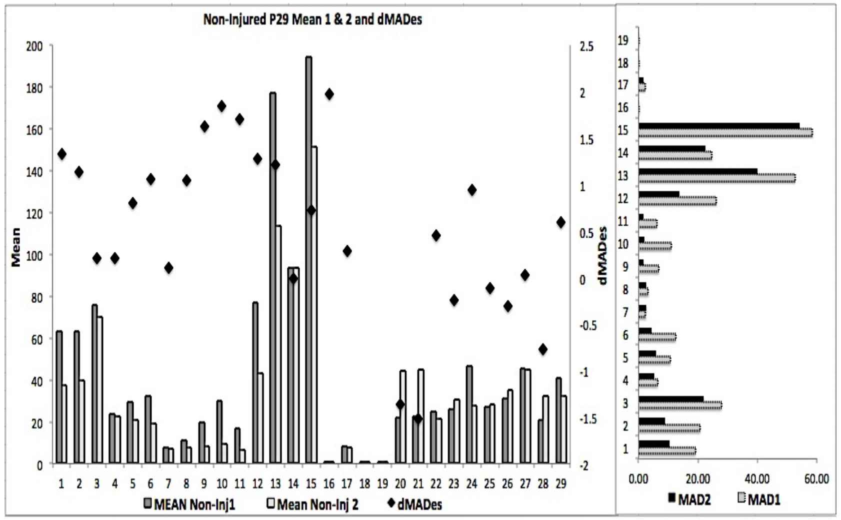

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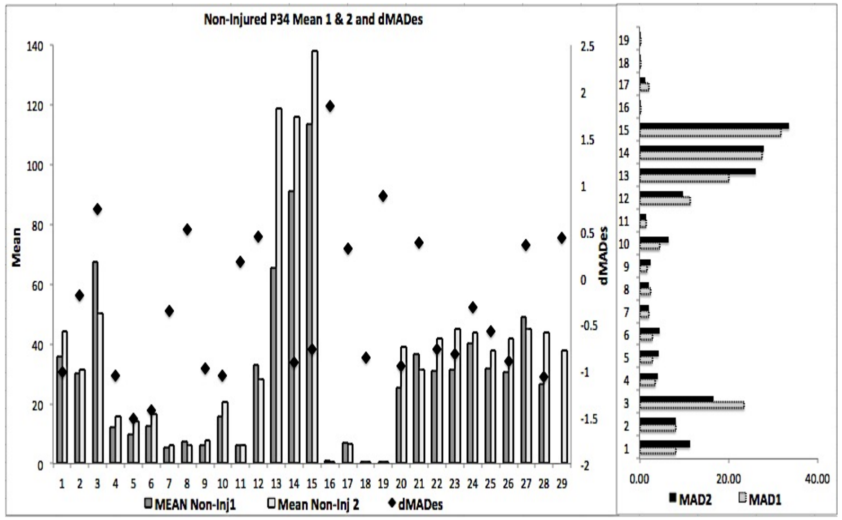

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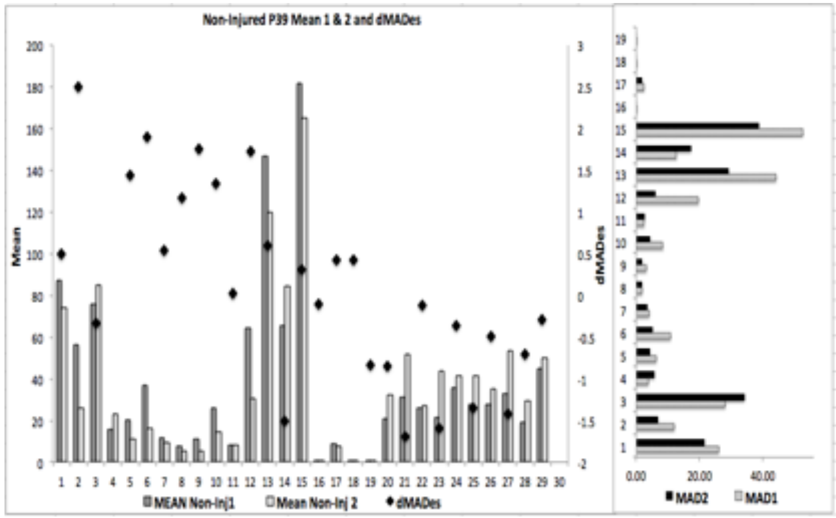

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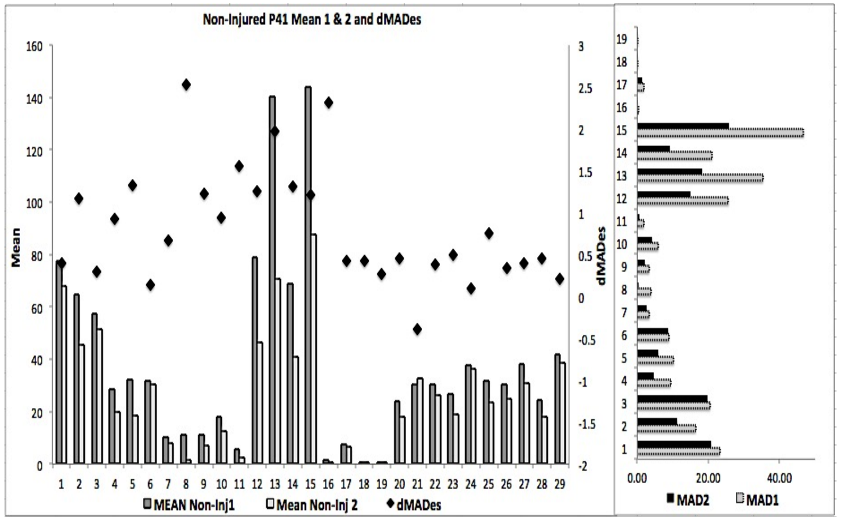

Participant 41

Appendix J

Pilot Study
Informed Consent Form & Participant Information

Title of Project: Pilot study to assess the Organic Motion analysis equipment's capacity to accurately measure human movement in a test-retest protocol

Principal Researcher: Paul Bell BSc (Hon) Osteopathy

Participant's printed name:

Name:…………………………………………………… Date:………./………/………

INTRODUCTION
We invite you to take part in a pilot research study, which will be undertaken by Paul Bell as part of a doctoral research study program at the University of Bath (U.K). The aim is to investigate the test-retest capacity of the proposed motion analysis system as a tool for motion analysis in research.
The assessment will be carried out at your place of work: The Osteopathic Centre clinic, The Arcade, Raffles Place in Singapore.
Taking part in this study is entirely voluntary. We urge you discuss any questions about this study with Paul Bell. If you decide to participate, you must sign this form to show that you want to take part.

Section 2. PROCEDURES
You must have read and signed this informed consent form prior to entry into the research trial. The assessment will involve five repetitions of you squatting down to a fixed point at normal office chair height. The motion analysis system will be fully closed down and then restarted and calibrated before the identical procedure is repeated a second time.

Section 3. TIME DURATON OF THE PROCEDURES AND STUDY
If you agree to take part in this study, your involvement will last approximately ten minutes.

Section 4. DISCOMFORTS AND RISKS
This assessment is extremely low risk, however you will be required to complete a pain scale questionnaire and will not be allowed to participate if you score above 0. If you experience any pain or discomfort during or following the assessment, please notify Paul Bell immediately.

Section 5. POTENTIAL BENEFITS
By participating in this research you will be contributing to future research that is aimed at identifying kinematic changes in spinal motion in sports people who have experienced injury.

Section 6. STATEMENT OF CONFIDENTIALITY

All personal data from the trial will be anonymised and stored on a password-protected computer; this includes measurements from the sensor equipment undertaken during the assessments. Signed consent forms will be locked in a fireproof cabinet and stored within the clinic of Paul Bell, located at The Osteopathic Centre Clinic, Bowmont Centre, Siglap, Singapore. Access to data will be limited to you and Paul Bell.

Section 7. COSTS FOR PARTICIPATION

You will not incur any costs for participation in this pilot study

Section 8. COMPENSATION FOR PARTICIPATION

There will be no financial compensation for participation in this pilot study.

Section 9. VOLUNTARY PARTICIPATION

Taking part in this research study is voluntary. If you choose to take part you have the right to stop at any time. If you decide not to participate or if you decide to stop taking part in the research at a later date, there will be no penalty or loss of benefits to which you are otherwise entitled.

Section 10. CONTACT INFORMATION FOR QUESTIONS OR CONCERNS

You have the right to ask any questions you may have about this pilot study. If you have questions, complaints, or concerns or believe you may have developed an injury related to this research, contact Paul Bell at [redacted] or email [redacted]

SIGNATURE AND CONSENT/PERMISSION TO BE IN THE RESEARCH

Your signature below means that you have received this information, have asked the questions you currently have about the pilot study. You will receive a copy of the signed and dated form to keep for future reference.

Participant: By signing this consent form, you indicate that you are voluntarily choosing to take part in this pilot study.

____________________	________	____	__________
Signature of Participant	Date	Time	Printed Name

Researcher (Paul Bell): Your signature below means that you have explained the research to the participant and have answered any questions about the research.

____________________	________	____	__________
Signature of Researcher	Date	Time	Printed Name

Adapted the: The National Centre for Complementary and Alternative Medicine (NCCAM), Informed consent template ((NCCAM), 2014)